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The role of focal length on lens aberrations with aperture variations.

Ulrich, Charles Henry.

Monterey, California. Naval Postgraduate School

Charles Henry Ulrich

THE ROLE OF FOCAL LENGTH ON LENS ABERRATIONS WITH APERTURE VARIATIONS

THE ROLE OF FOCAL LENGTH ON LENS ABERRATIONS

WITH

APERTURE VARIATIONS

A Thesis

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by

Charles Henry Ulrich, B.Sc.

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SUMMARY

This study investigated the effect of a reduction of relative lens aperture upon the major lens distortions for photogrammetric cameras of varying focal lengths. The studies reveal that chromatic aberration and spherical aberration decreased, curvature of field increased, while radial distortion and astigmatism were unaffected.

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I. PURPOSE AND SCOPE

The investigations into the role the focal length of a photogrammetric camera plays in the quality of the image generated has been pursued by several researchers at The Ohio State University. These studies into the selection of a "best" focal length for a photogrammetric camera for a specified image purpose include those of Captain Roger M. Ryan[8]*, Lieutenant Charles F. Tomajczyk[10] and Captain Byron S. Fitzgerald[4].

As is apparent, other things that affect the generated image of the photogrammetric camera are variable and one of these items is the lens aperture[11]. For many cameras this is an adjustable or, at least, a changeable feature. Data were available from Captain Fitzgerald's study, so it was considered worthwhile to repeat this research using the same lenses but with a different aperture setting, thus giving a base of comparison from which to help in the selection of a "best" combination of focal length and aperture for a photogrammetric camera. The specific purpose of this report is to determine the effect upon the aberrations of the generated images of photogrammetric cameras of varying focal lengths caused by a variation of the aperture of the lens. The three lenses tested were of similar design, differing only in focal length.

*References appear in the Bibliography

As all of the results are based upon only a single lens for each focal length, no statistical conclusions pertaining to the characteristics of a particular lens or group of lenses are claimed. Each lens was assumed to be representative of a type and sufficient repetitions of data results were taken until the quality of a particular measurement was reasonably verified. In all data tables the standard deviation of the mean of the readings are listed, and they are computed in the following manner:

$$\text{Standard deviation} = \pm\sqrt{\frac{[vv]}{n(n-1)}}$$

where

v = deviation

n = number of observations

In every case the weight of a single observation was assumed to be one and the covariance to be zero.

The quality of the measurements is therefore strengthened as to precision; however, the accuracy is governed by the physical quality of the instruments used and although these were of generally high quality and reasonable care was exercised, no claim beyond that pertaining to accuracy is made.

For purposes of reference, all of the previous comparison tests were conducted at a relative aperture of f/6.3. All of the tests which are described and whose results are tabulated in this report were conducted at a relative aperture of f/8.

2. EQUIPMENT USED

The materials to be tested were three type I, f/6.3, BAUSCH AND LOMB METROGON lenses with effective focal length of 3 inches, 6 inches and 12 inches. (Serial numbers: 3 inch = No. BF 2309; 6 inch = No. MS 3871; 12 inch = DF 9431.) (See Figure 1.)

Control of the aperture was to be extremely important so initial apertures were checked, and the new apertures were set, utilizing a BAUSCH AND LOMB ILLUMINATION ANALYZER MODEL 3 - (AF contract 33(601)-2440). (See Figure 2.)

All of the filters used were Kodak Wratten. These were 2 inch by 2 inch glass filters from set No. 3015 and were always positioned between the light source and the target. Filter No. 74 was used as a pass filter in the tests requiring it because it had sharp cut-off characteristics, it passed a mid-frequency band of light, it was not irritating to the eye after continued viewing and it also was the filter used in the comparison study[4]. Filters Nos. 47, 45a, 75, 65, 60, 74, 73 and 25 covered the visible spectrum and had acceptable characteristics as shown in Table I.

The photographic work upon the 12 inch focal length lens was done on a permanently mounted test camera and collimator. This assembly was composed of a lens test camera Serial No. L-1 (see Figure 3), manufactured by the JAM HANDY ORGANIZATION, DETROIT, MICHIGAN, and a collimator, manufactured by the F. W. FECKER DIVISION of THE AMERICAN OPTICAL COMPANY, with a focal length of 14 feet: f/10.5 (see Figure 4). During the course of the research, this unit was moved to a new location and

all chromatic aberration and spherical observation tests were made on the same equipment, but at a new location.

The Nodal Slide Optical Bench (Serial No. 600) was manufactured by the GEOPHYSICAL INSTRUMENT COMPANY and had an effective focal length of 48 inches; f/12. For all tests, the observation microscope was used with a 38 mm objective lens. (See Figure 5.)

A Wild T-4 Goniometer (Serial No. 26) was used for distortion measurements. (See Figure 6.) In conjunction with the Goniometer, a Watts Auto-Collimator (Serial No. 79538) with an effective focal length of 18 inches was used (see Figure 7) for alignment of graduated target plate No. 13224-104. The flash discharge lamp was an Ascorlight, Model A 6145, Series 600, manufactured by the AMERICAN SPEED LIGHT CORPORATION.

All of the equipment used was located at the Wright-Patterson Air Force Base, Ohio and was in the custody of the Photo-Optical Section of the Avionics Laboratory of that facility.

Figure 1. Lenses

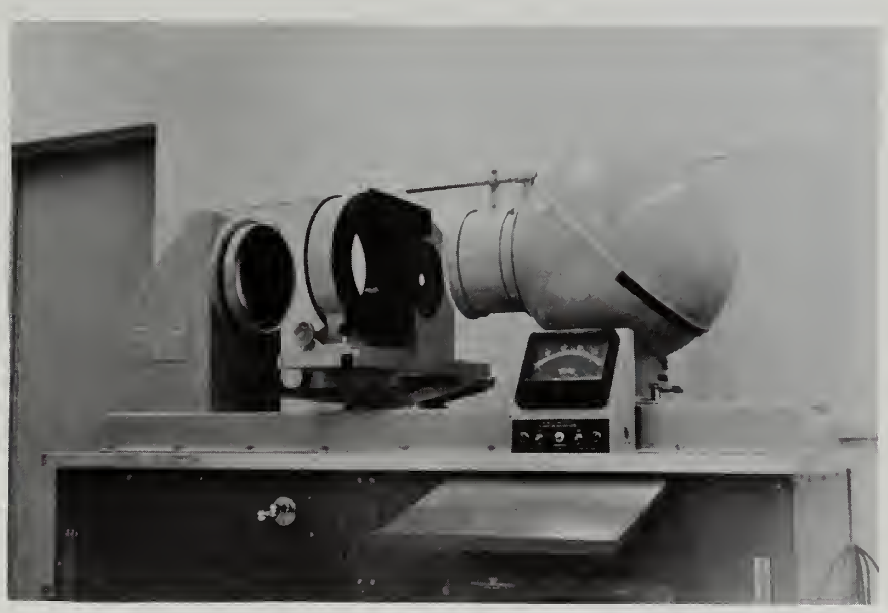


Figure 2. Illumination Analyzer

Figure 3. Medium Test Camera

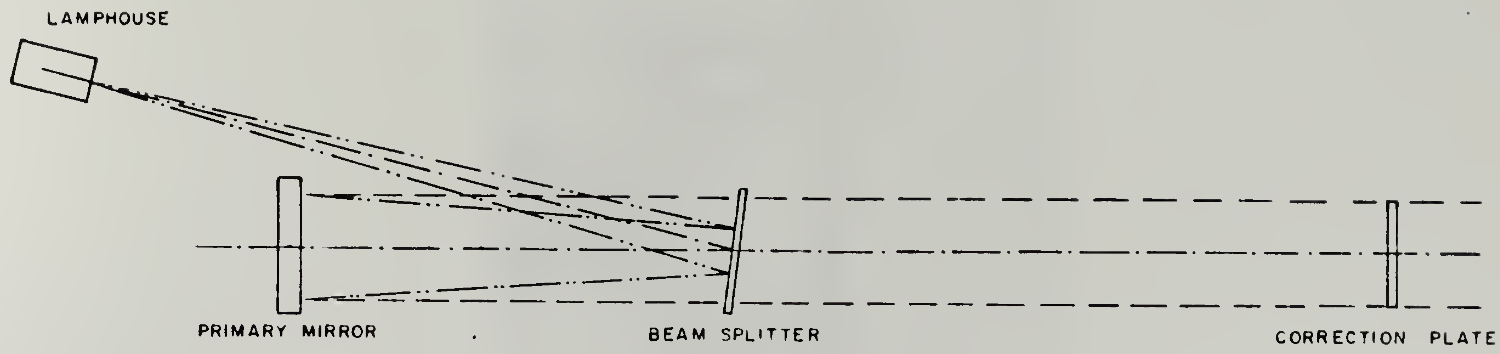


Figure 4. Schematic Diagram of Collimator Used in Conjunction with Medium Test Camera

Figure 5. Nodal Slide Bench

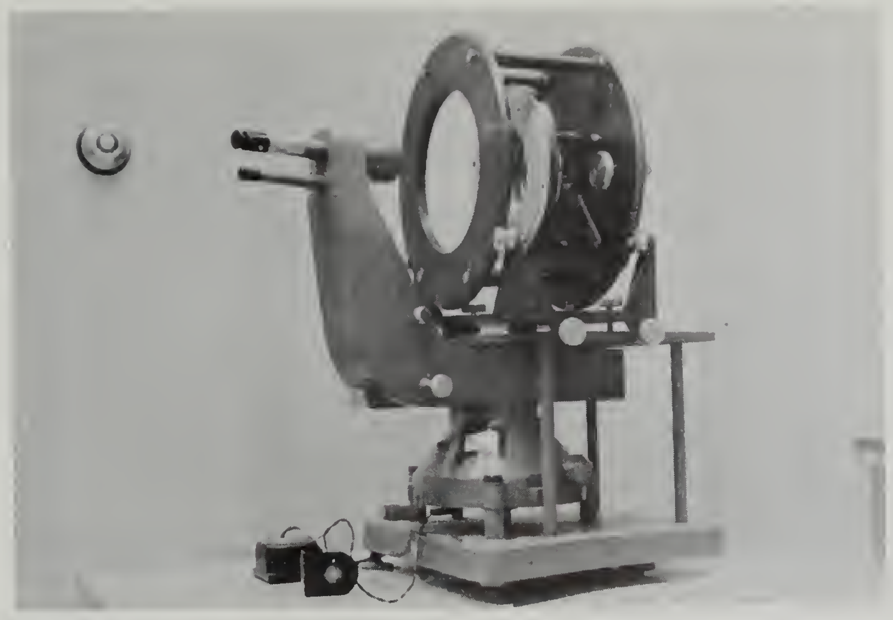


Figure 6. Wild T-4 Goniometer

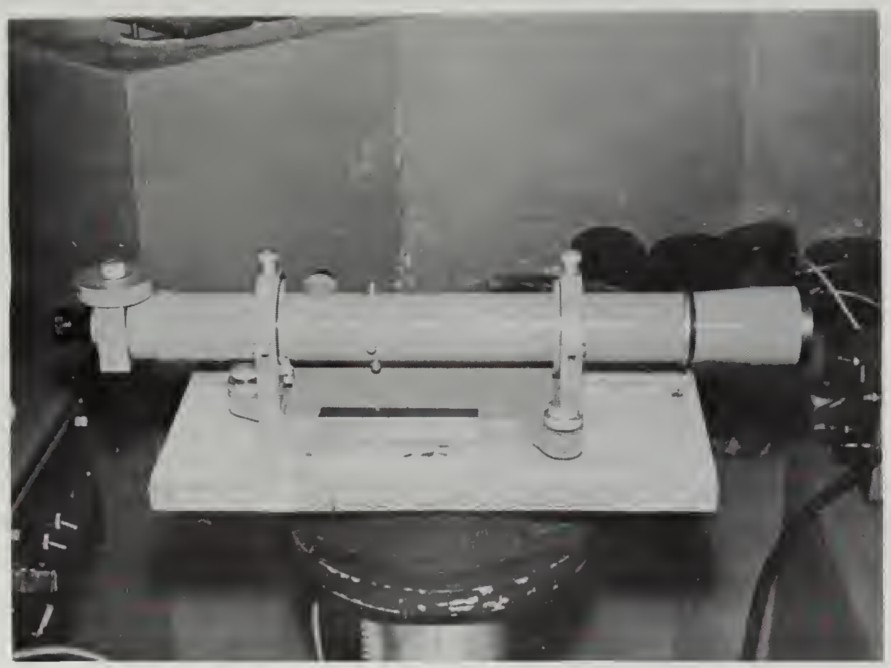


Figure 7. Auto-Collimator

3. ADJUSTMENT OF LENS APERTURES

3.1 Purpose of Adjustment

The Metrogon lens, as developed by the Bausch and Lomb Optical Company of Rochester, New York, was the result of an effort to adopt the wide-angle photogrammetric lens produced by R. Richter of the Carl Zeiss Company to American needs[7]. It is a multiple element lens compounded to produce a wide-angle lens that would be relatively fast, nearly "distortion-free" and have a reasonable correction of other aberrations within the usable field. Since its development during the 1930's, it has been superseded by other and better lenses[9]. However, it is of basic modern design, it is available in several focal lengths, its distortions are relatively large by today's standards, and it was convenient to measure them during this research.

The relative aperture of a lens (also called the speed, or f-number) is defined as the ratio of the equivalent focal length to the aperture[1]. An example of this would be for a lens of 8 inch focal length and 1 inch diameter aperture; the relative aperture would be f/8. The amount of light that the sensitized surface or film in a camera receives from an object of given light intensity depends greatly on relative aperture. The depth of field is also affected by aperture. For a given lens, an optimum focal position can be found by experimentation. The allowable or measurable distortions then create a visual circle on either side of the exact focus. As is apparent from the proportionality of the cones of light involved, as the lens aperture is reduced, the position of the allowable circle of light in the image will

move away from the position of best focus, thus creating a greater "depth" of focus.

The basic lens assembly is shown to scale for a 6 inch focal length, f/6.3, Metrogon lens on Page 56. As can be seen in this figure, there is a space between the lens elements which is large enough to install an aperture controlling diaphragm without altering the basic geometry of the lens. This was desired in order to provide a test instrument with which to investigate the amount the lens distortions would be affected by a reduction in relative lens aperture. All lenses tested were designed with relative apertures of f/6.3, therefore, the installation of a reduced aperture would show only how the original lens would be affected, and the data collected is not intended to represent a Metrogon type lens designed for best performance at f/8.

3.2 Aperture Adjustment Procedure

The 3 inch focal length Metrogon lens was equipped with an adjustable internal diaphragm, therefore, the problem of resetting its aperture was greatly simplified. Aperture plates were constructed from thin, dark-colored cardboard for the other two lenses. The relative aperture for the test was selected to be f/8, so the diameter of the hole in the diaphragm was computed as follows:

(12 inch focal length lens) $f/8 = \frac{12}{x}$; $x = 1.50$ inch

(6 inch focal length lens) $f/8 = \frac{6}{x}$; $x = .750$ inch

These cardboard plates were constructed, the lens bodies disassembled, the diaphragms inserted and centered, and the lenses reassembled carefully, to insure that no new error was introduced.

At this point some manner of verification was required to determine if the apertures were centered and were of correct size in order to make any later results obtained meaningful. It was decided to cut test aperture plates with hole diameters of .375 inch, .750 inch and 1.50 inch for use with the BAUSCH AND LOMB Illumination Analyzer Model 3 (see Figure 2). This instrument utilized a variable density diffused light source. The light was passed through a 60 inch, f/6.0 collimating system consisting of a light path folded by two first-surface mirrors to reduce the size. This light beam is of a high degree of illumination uniformity across the collimated beam. The light passes through a lens-diaphragm combination and is received by a photo-electric detector which picks up the light beam and indicates a value on a sensitivity meter.

The original light source in instantly adjustable so that meter readings can be changed by the turn of a knob.

Each lens was compared with the value of light passing through the lens at f/6.3 set at a meter reading of 100 per cent, and that at f/8 as 61 per cent meter reading at the same light intensity. The numerical value was arrived at experimentally, utilizing all of the lenses with known apertures of f/6.3 and then fixing the reduced aperture plates over the lenses to get the light reduction value. All of the final aperture settings agreed to a measuring precision of the meter which was finer than 5 per cent.

As the aperture was set in a relatively permanent fashion in the 6 inch and 12 inch focal length lenses, these were now ready for further testing. The 3 inch focal length lens with the adjustable diaphragm collar, had this collar taped securely and a scribe mark placed on the collar itself for visual checking for motion of the collar.

One further comparison was made concerning the variation in transmittance of light between the lenses. Each lens was mounted in the Illumination Analyzer and the light source adjusted so that the open aperture with no lens caused a meter reading of 100 per cent. Then the lens was placed in the path of the collimated light and the meter read again. The results of these tests are shown in Figure 8. A further calculation was based on the transmittance of the light by the lenses. Transmittance is defined as "the ratio of light that passes through a lens to the light that passes through an open circular hole having the same diameter as the effective aperture of the lens"[12]. From this value

it is possible to compute the T-number of the lenses. T-number is defined as

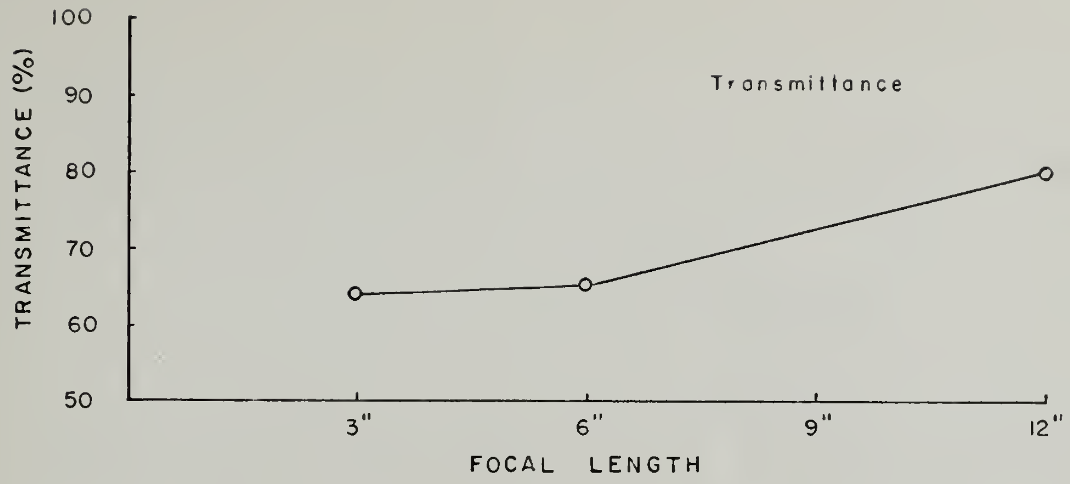
$$\text{T-number} = \sqrt{\frac{(\text{f-number})^2}{\%\ \text{transmittance}}}$$

The results of this computation are also shown in Figure 8.

3.3 Comments

The setting of the reduced apertures was completed with sufficient accuracy to validate further tests based upon them. The Illumination Analyzer was a simple machine to operate and gave excellent results. It could be used as a test tool for many kinds of lens analysis to great advantage.

It is ascertained from the results obtained that the increased size of the aperture of a 12 inch focal length lens passes a significantly greater amount of light than that passed by the 6 inch and 3 inch focal length lenses. It is apparent, however, that the increase of light passed is not a linear function but that the percent of light passed increases with increased focal length. The relative aperture and focal.length are mutually involved and not enough data is available to draw any conclusions about their relationship. This could be the subject for more detailed research on this aspect of light transmittance of lenses of varying focal length.



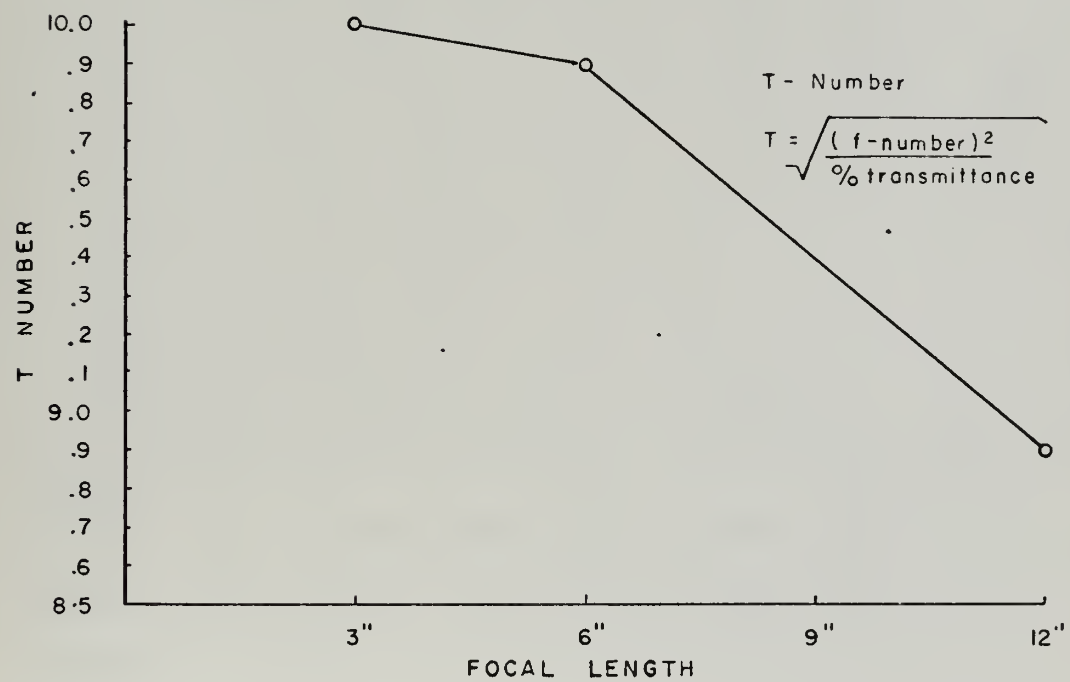


Figure 8. Graphs of Transmittance and T-Number of Metrogon Lenses of Varying Focal Length

TABLE I

FILTER CHARACTERISTICS

Wave Length (m μ)	PERCENT TRANSMITTANCE 47	45a	75	65	60	74	73	25
400	7.80							
10	17.4							
20	34.0							
30	47.0	1.00						
40	50.3	8.81		0.20				
50	48.3	17.4		2.04	0.19			
60	43.4	20.9	1.97	9.0	1.38			
70	36.2	21.6	10.00	19.1	5.38			
80	28.5	20.5	17.4	27.3	15.0			
90	19.6	18.0	18.0	31.9	32.0			
500	11.3	14.4	13.0	33.6	48.4			
10	5.64	10.1	7.35	32.4	57.2	0.96		
20	1.91	5.60	3.20	28.1	59.2	7.95		
30	0.36	2.52	0.83	21.3	55.5	14.6		
40		0.64	0.14	13.3	47.5	12.9		
50		0.10		6.6	36.8	7.60		
60				1.82	25.2	3.06	2.24	
70				0.43	14.4	0.83	5.97	
80					6.3	0.12	4.56	
90					1.82		2.00	12.6
600					0.48		0.56	50.0
10					0.10		0.10	75.0
20								82.6
30								85.5
40								86.7
50								87.6
60								88.2
70								88.5
80								89.0
90					2.10			89.3
700		0.20	0.14		8.70			89.5
Dominant Wave Length	470.1	483.5	490.5	501.3	520.0	538.0	576.0	617.2
Excitation Purity	96.0	90.5	92.5	74.0	59.5	93.5	100.0	100.0
% Luminous Transmittance	1.2	1.5	1.01	6.6	20.7	3.34	1.41	22.5

4. LONGITUDINAL CHROMATIC ABERRATION

4.1 Purpose of Test

This test was made to determine the amount of longitudinal chromatic aberration present on the three lenses of different focal lengths for comparison with the aberration measured with the same lenses but at a different relative aperture. This was done by measuring the variation in "back focal distance" for light of different colors or wave lengths as this variation is the manner in which longitudinal chromatic aberration is specified[1].

4.2 Testing Procedure

The Medium Test Camera (see Figure 3) was set up for each lens. Instead of a film holder, a low power (10X) compound microscope was installed in the film holder bracket. The light source used was a white incandescent bulb in an appropriate holder. A Kodak Wratten pass filter was placed between the light and a high contrast resolving power test target (see page 16). The filter characteristics are displayed graphically on page 60. The target was placed at the principal focus of the 14 foot effective focal length collimator (see Figure 4). The lens was then placed in the circular lens clamp of the test camera bench (see Figure 3). It was aligned in such a manner that the lens axis was situated in the collimated beam of light and was also perpendicular to the plane of the film holder bracket and then the lens and the bracket were secured.

As each filter was inserted into the filter plate holder, the test microscope was moved longitudinally until it was in the position yielding maximum resolution of the test target. This position was

recorded as a reading on a dial indicator affixed to the lens holder with its measuring protrusion resting against the movable film holder bracket. The longitudinal chromatic aberration for a particular color (wave length) was then defined as the difference between this setting and that for the reference color which was taken as that reading recorded for the shortest wave length. For this test, the reference was the wave length passed by Wratten Filter No. 47 which is dominant at 470.1 millimicrons. This selection of reference allowed all aberrations to be measured as positive and allowed also simplified graphic portrayal of the results. As the entire list of selected filters was utilized, the lens was then replaced with the next and the microscope and dial indicator were reset at the new point of maximum resolution and the test continued.

4.3 Comments

The compared results of the three lenses are shown in Figure 9. This graph is plotted from the data shown in Table II. Although a comparison of these results with those of the lenses with relative aperture settings of f/6.3 indicate a similarity in the shape of the chromatic aberration curve, a significant reduction in this aberration is apparent. This indicates that for the same lens, a reduction in relative aperture results in a reduction in the longitudinal chromatic aberration.

According to the international photogrammetric expert, Dr. B. Hallert, all of the calibrations and distortion measurements should be done photographically and using temperature and other conditions similar to the actual condition which would exist at the time of use

of the lens in a camera[6]. This was not possible due to expense, equipment limitations and also to the fact that the same methods had to be used as those used in the comparison study in order to produce data of value. Therefore, none of the values obtained for the various distortions are intended to provide statistical verification for the quality of a specific lens; but rather to provide numerical research data for the investigation of the role of varying the focal length and also the relative aperture of a photogrammetric camera upon the various distortions of that camera.

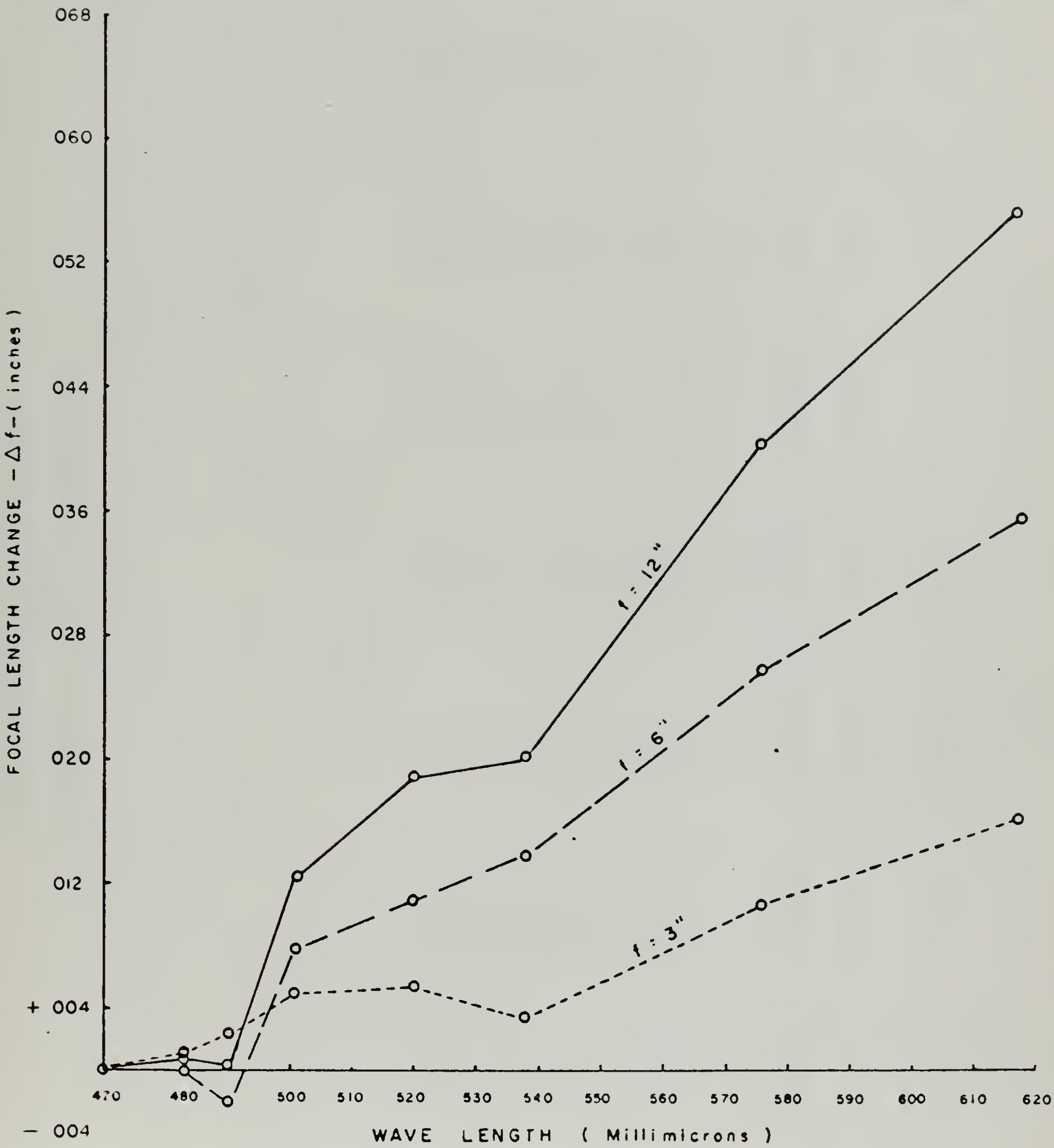


Figure 9. Comparison of Focal Length Changes of Three Metrogon Lenses of Varying Focal Length Due to Longitudinal Chromatic Aberration

TABLE II

DIAL READINGS AND COMPUTATIONS
FOR
LONGITUDINAL CHROMATIC ABERRATION
(Inches)

Filter Number	47	45a	75	65	60	74	73	25
Wave Length ($m\mu$)	470.1	483.5	490.5	501.3	520.0	538.0	576.0	617.2
			METROGON (f=12 Inches)					
OBS								
1	.5700	.5709	.5672	.5799	.5879	.5909	.6109	.6256
2	.5707	.5701	.5705	.5845	.5905	.5892	.6093	.6258
3	.5710	.5720	.5694	.5799	.5886	.5901	.6105	.6255
4	.5705	.5701	.5703	.5810	.5898	.5901	.6102	.6250
5	.5700	.5712	.5710	.5882	.5897	.5904	.6104	.6250
6	.5698	.5711	.5703	.5849	.5872	.5904	.6099	.6254
7	.5697	.5712	.5724	.5832	.5895	.5903	.6107	.6265
8	.5691	.5716	.5709	.5821	.5892	.5914	.6109	.6254
9	.5696	.5691	.5700	.5812	.5897	.5903	.6109	.6262
10	.5714	.5723	.5708	.5808	.5896	.5903	.6103	.6260
Mean	.5702	.5710	.5703	.5826	.5892	.5903	.6104	.6256
Std.Dev.	$\pm$.000223	$\pm$.000306	$\pm$.000125	$\pm$.000839	$\pm$.000313	$\pm$.000134	$\pm$.000124	$\pm$.000156
Diff.	---	+.0008	+.0001	+.0124	+.0190	+.0201	+.0402	+.0554
Std.Dev. Diff.	$\pm$.00022	$\pm$.00038	$\pm$.00027	$\pm$.00087	$\pm$.00039	$\pm$.00027	$\pm$.00027	$\pm$.00027

TABLE II

DIAL READINGS AND COMPUTATIONS
FOR
LONGITUDINAL CHROMATIC ABERRATION
(Inches)

(continued)

METROGON (f = 6 Inches)

OBS								
1	.5850	.5863	.5832	.5918	.5944	.5977	.6130	.6206
2	.5858	.5849	.5873	.5931	.5961	.5994	.6113	.6212
3	.5852	.5846	.5839	.5930	.5966	.5998	.6110	.6208
4	.5864	.5847	.5867	.5932	.5975	.5998	.6119	.6212
5	.5859	.5855	.5857	.5937	.5980	.5996	.6114	.6207
6	.5852	.5853	.5848	.5954	.5968	.6000	.6114	.6208
7	.5856	.5853	.5853	.5945	.5970	.5995	.6110	.6210
8	.5857	.5852	.5857	.5933	.5965	.5997	.6107	.6215
9	.5854	.5862	.5852	.5917	.5961	.5999	.6107	.6218
10	.5848	.5866	.5850	.5943	.5964	.5988	.6106	.6215
Mean	.5855	.5855	.5853	.5934	.5965	.5994	.6113	.6211
Std.Dev.	±.000151	±.000220	±.000382	±.000363	±.000305	±.000220	±.000228	±.000126
Diff.	---	0	-.0002	+.0079	+.0110	+.0139	+.0258	+.0356
Std.Dev. Diff.	±.00015	±.00027	±.00041	±.00039	±.00035	±.00071	±.00027	±.00020

TABLE II

DIAL READINGS AND COMPUTATIONS
FOR
LONGITUDINAL CHROMATIC ABERRATION
(Inches)

(continued)

METROGON (f = 3 Inches)

OBS								
1	.3291	.3333	.3281	.3350	.3350	.3339	.3421	.3456
2	.3318	.3315	.3288	.3355	.3364	.3346	.3418	.3462
3	.3304	.3328	.3292	.3367	.3378	.3341	.3409	.3480
4	.3311	.3318	.3291	.3363	.3372	.3334	.3421	.3473
5	.3310	.3316	.3293	.3365	.3365	.3345	.3416	.3470
6	.3308	.3321	.3286	.3360	.3354	.3346	.3420	.3464
7	.3308	.3312	.3287	.3359	.3361	.3342	.3421	.3482
8	.3320	.3317	.3288	.3362	.3366	.3349	.3421	.3472
9	.3317	.3323	.3288	.3360	.3368	.3342	.3415	.3475
10	.3315	.3331	.3286	.3362	.3362	.3344	.3420	.3477
Mean	.3310	.3321	.3288	.3360	.3364	.3343	.3418	.3472
Std.Dev.	±.000268	±.000227	±.000110	±.000156	±.000272	±.000134	±.000124	±.000263
Diff.	---	+.0011	-.0022	+.0050	+.0054	+.0033	+.0108	+.0162
Std.Dev. Diff.	±.00027	±.00035	±.00028	±.00032	±.00039	±.00030	±.00030	±.00038

5. SPHERICAL ABERRATION

5.1 Purpose of Test

This test was conducted to measure the spherical aberration of the lenses. Spherical Aberration is the optical defect in which the rays of light through different narrow circular zones of the lens, concentric with the optical axis from an axial object point, do not come to focus at the same point. The results from the three lenses with relative apertures of f/8 were then to be compared with the results of a similar test made at a relative aperture of f/6.3.

5.2 Testing Procedure

The same equipment was used for this test as was used previously to measure longitudinal chromatic aberration and in much the same way. It was important for this test to avoid any chromatic aberration so the same filter was used for all phases. For experimental purposes, white light was attempted, but the chromatic aberration was so great the experiment failed. Therefore, a suitable Kodak Wratten filter was used. This was the same filter as was used in the initial study for comparison, No. 74. This filter has sharp cut-off characteristics, is pleasing to the viewers eye, and also passes a wave length of light which is about in the middle of the visible spectrum.

The Medium Test Camera, high contrast resolving power test target, and 14 foot effective focal length collimator were also used as they were previously.

This test revealed an apparent problem caused by the effect of reducing the aperture of the lenses which resulted in a great light loss

through the lens. So much light was blocked that only two zones could be considered. An intricate system of blocking rings were constructed and tried, but it was impossible to get enough light through the lenses to accurately determine a focus point of the target by visual means except for several combinations. The points determined were with the lens uncovered, with a small area on the lens axis and with the central area blocked, but with light passing through the remaining area. The areas of the zones were as follows:

12 inch focal length	inner circle = 36% total area
6 inch focal length	inner circle = 59% total area
3 inch focal length	inner circle = 59% total area

A determined effort was made to make all the areas similar; however, physical size of the shorter focal length lenses impeded this.

Sufficient data were accumulated to show grossly the effect of the spherical aberration and is presented in Table III. The comparison of the lenses is made in the graph drawn as Figure 10.

5.3 Comments

The results obtained from this test indicate that the greater the focal length, the greater will be the spherical aberration.

It is of interest here to point out that the reduction in aperture for the 12 inch focal length lens so affected the depth of field for this lens that a greater adjustment was required to bring the target into focus from no light restriction to that where the center area of the lens only was open, than from the center area to that of the outer portion of the lens. This test was repeated several times to verify

these results and are illustrated in the portion of Figure 10 pertaining to the 12 inch focal length lens. This characteristic was not found in the other two lenses and as this was not a test done in the comparison work, there is no corroboration. This point may be of interest to an investigation of the 12 inch focal length lens if it were done in detail by subsequent research.

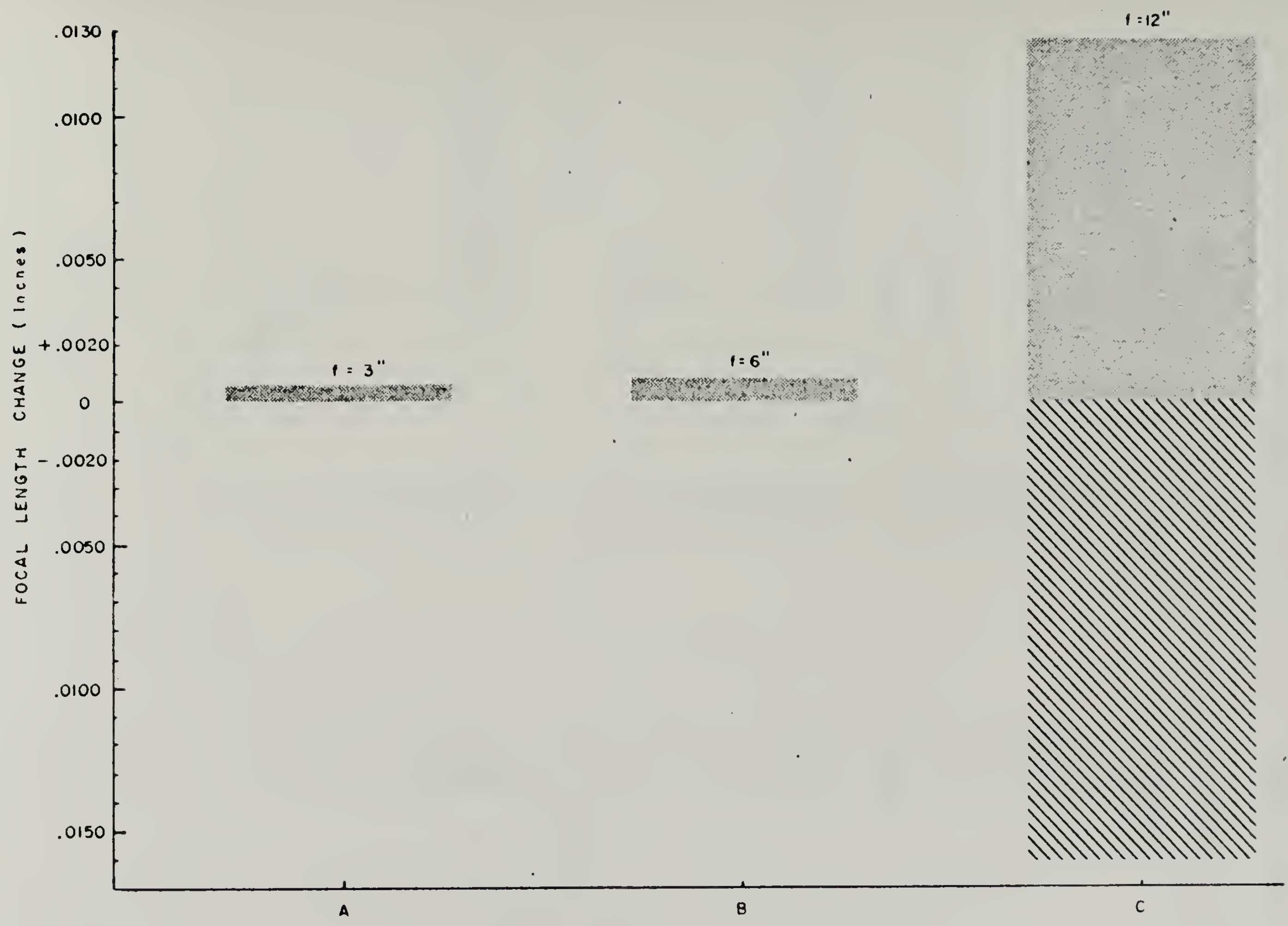


Figure 10. Graph of Focal Length Changes
Caused by Spherical Aberration in Metrogon Lenses
of Varying Focal Length

TABLE III

SPHERICAL ABERRATION DATA FOR METROGON LENS

	3" Focal Length Inches	6" Focal Length Inches	12" Focal Length Inches
I (Clear lens)	.3341 .3341 .3343 .3343 .3342	.1428 .1430 .1434 .1431 .1430	.1398 .1398 .1397 .1405 .1401
Mean	.3342	.1431	.1400
Std.Dev.	±.00004	±.00010	±.00016
II (Light through area on lens axis only)	.3339 .3343 .3341 .3343 .3346	.1427 .1429 .1430 .1431 .1432	.1554 .1554 .1567 .1564 .1566
Mean	.3342	.1430	.1561
Std.Dev.	±.00012	±.00009	±.00029
Area of hole	.065 sq.in.	.261 sq.in.	.637 sq.in.
III (Light through outer lens area only with center area blocked)	.3336 .3340 .3336 .3334 .3337	.1423 .1423 .1422 .1423 .1420	.1428 .1429 .1432 .1447 .1432
Mean	.3337	.1422	.1434
Std.Dev.	±.00010	±.00006	±.00035
% of lens area blocked	59%	59%	36%
Δ Focal length (I, II)	0	.0001	.0161
Std. Dev.	±.00013	±.00014	±.00031
Δ Focal length (II, III)	.0005	.0008	.0127
Std. Dev.	±.00016	±.00011	±.00046

6. ASTIGMATISM

6.1 Purpose of Test

Astigmatism results from the fact that rays of light which enter a lens radial to the optical axis produce an image surface different from that produced by light entering the same lens in rays which are tangent to circles concentric to the optical axis. The non-coincidence of these two image surfaces is usually called "astigmatism" and their amount of separation measured parallel to the optical axis is called the "astigmatic difference". The average surface between the two image surfaces is that surface least affected by the orientation of the ray generating object and is called the "surface of least confusion." None of the three image surfaces are a true plane and the difference of the surface of least confusion from a true plane is termed "curvature of the field."[1]

The reduction of light which can pass through a camera lens, caused by a reduced relative aperture, could affect the amount of astigmatism, so this test was done to obtain data for comparison with results previously obtained on the same lenses but with larger relative aperture.

6.2 Testing Procedure

The size of the 12 inch focal length lens required that it be tested on the Medium Test Camera (see Figure 3) and equipment limited this to photographic methods. This method was costly and time consuming compared to performing the test on the Nodal Slide Bench which was available. The testing period was also concurrent with the physical location changing of the test camera, therefore, only the lens of 12 inch focal

length was tested photographically. Photographic and visual methods had been compared satisfactorily previously.[4]

For this test, the light source used was a flash discharge lamp which could be remotely triggered from the test stand. A Wratten No. 74 filter was then placed between the light and a high resolution resolving power test target which was situated at the principal focus of the 14 foot effective focal length collimator. The lens was clamped in the lens holder in the collimated beam of light. The film holder was loaded with a strip of special high resolution (SO 243) Kodak film. The film holder was positioned in its bracket perpendicular to the optical axis of the lens and was placed against a dial indicator so that the film position could be changed with respect to the lens in a direction parallel to the optical axis of the lens and the amount of change measured and recorded. The entire apparatus containing the lens and the film holder was mounted on a steel beam that was geared to a measuring arc and could be swung to a position 45° on either side of the optical axis of the lens. The film was held in the film holder bracket by a vacuum pump attached directly to the unit with a plastic hose.

The actual conduct of the test was made in a dark room by triggering the flash discharge light to get an exposure on the film strip. Exposures were made at every 5° from the axis out to and including 40° on either side of the axis. A typical run would consist of an exposure at each of the angles and then repositioning the film plate holder enough to cause the next set of exposures to occur at a different place on the film in use, coupled with advancing the film holder parallel to the optical axis an amount .002 inches as measured on the dial indicator.

By making the exposure strips as close together as practical, it was possible to get fourteen rows of exposures for each strip of film. To control the intensity of the light so that satisfactory results could be obtained at the extreme angles off axis where the amount of light passing through the lens is decreased due to the cosine^4 law, the flash discharge lamp was switched from half power to full power at all angles above 25° off axis. The developing of the film was done immediately on completion of a strip to investigate the results. The difference between the position of best focus, which was determined by selecting the exposure with the highest resolution for the radial and tangential lines of the target, is the astigmatic difference. The resolutions are shown graphically in Figure 11.

The Nodal Slide Bench (see Figure 5) was used for the tests on the 3 inch focal length and the 6 inch focal length lens. The lens undergoing test was set up in the bench lens holder with an observing microscope positioned behind it. An incandescent light was directed through a Wratten No. 74 filter and a high resolution resolving power test target located at the principal focus of the 48 inch effective focal length collimator. The lens was then positioned experimentally so that the vertical axis of lens rotation of the holder coincided with the rear node of the lens. Concurrently, the lens was fixed so that its optical axis was parallel to the collimated light rays as well as coincidental to the objective lens axis of the observing microscope. This allowed the lens to be rotated about the vertical axis through its rear node while permitting the viewing microscope to be adjusted longitudinally until the test target would be in focus. By recording the

value of the distance between the rear node of the lens and the position of best focus in the viewing microscope for both radial and tangential lines, the data shown in Tables IV and V were gathered. As the measurements were not made along the optical axis, it was necessary to convert these distances to this axis. This was done by multiplying the length determined by the cosine of the angle between the optical axis and the microscope axis. Readings were taken at 5° increments about the optical axis until the image was cut off by the apparatus and were improved in precision by the use of a low power jeweler's eye piece. Graphs of the results are shown as Figures 12 and 13.

6.3 Comments

The astigmatic difference for the three lenses are computed graphically in Figure 14.

The photographic method was potentially the best method for this test; however, it is believed to yield the poorest results. This is because there was so much change in focal distance for the off-axis exposure that it was nearly impossible to conceive of a realistic sequence where the entire range of angles would be recorded on one film strip. There appeared to be so much variation in film, developer and developing methods that it was difficult to compare different film strips in a logical sequence. The resolution targets had to be observed under a 20X laboratory microscope to discern details and at this enlargement of a negative that began at about 1/8 inch by 1/8 inch in actual size; it was apparent that comparison between film strips was very much weaker than comparison of exposures on a single film strip.

7. CURVATURE OF THE FIELD

7.1 Purpose of Test

This test was conducted to measure the distance between the mean focal plane or "surface of least confusion" for a lens, and that of a true plane[1]. It was done to compare the results obtained for three lenses of varying focal lengths with relative apertures of f/8 to the results obtained with these same lenses but with a relative aperture of f/6.3.

7.2 Testing Procedure

This test was done in the same manner as the astigmatic tests previously described. The same data were employed to complete the results. As the astigmatic difference is defined as the difference in focal distance between the surface of best image focus for radial and tangential lines of the test pattern, the average or mean surface between these surfaces define the curvature of the field. The curve representing curvature of the field distortion is shown in Figure 15. This is a mean curve representing the best image surface for radial and tangential lines.

7.3 Comments

The scale selected for Figure 15 is designated plus and minus to provide rapid comparison with the similar graph of the work conducted on the lenses with relative apertures of f/6.3. These values have no relationship with the actual focal distances which would be obtained if the lenses were installed in a camera body.

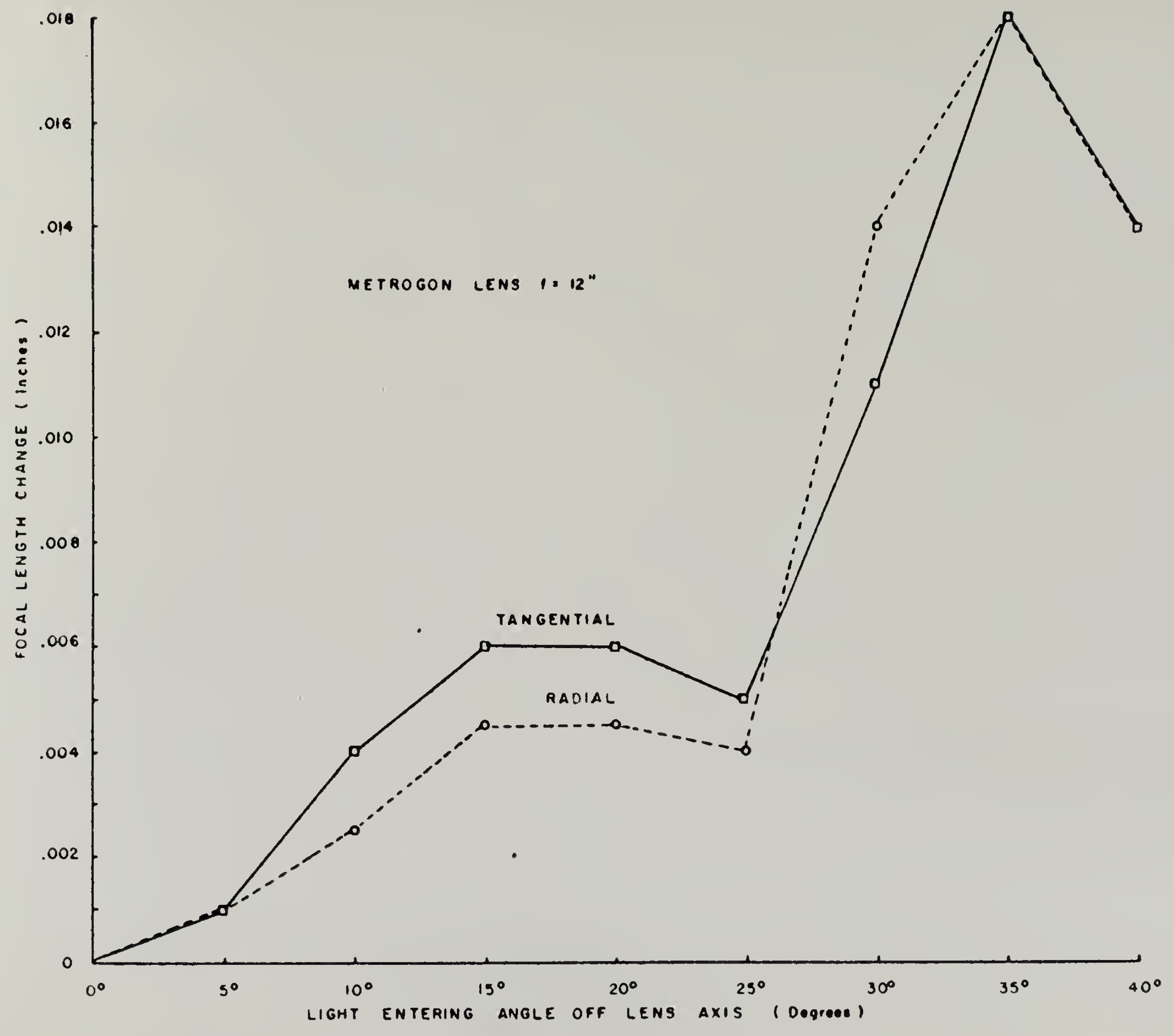


Figure 11. Graph of Focal Length Changes to Give Best Focus for Radial and Tangential Lines. Metrogon Lens f = 12"

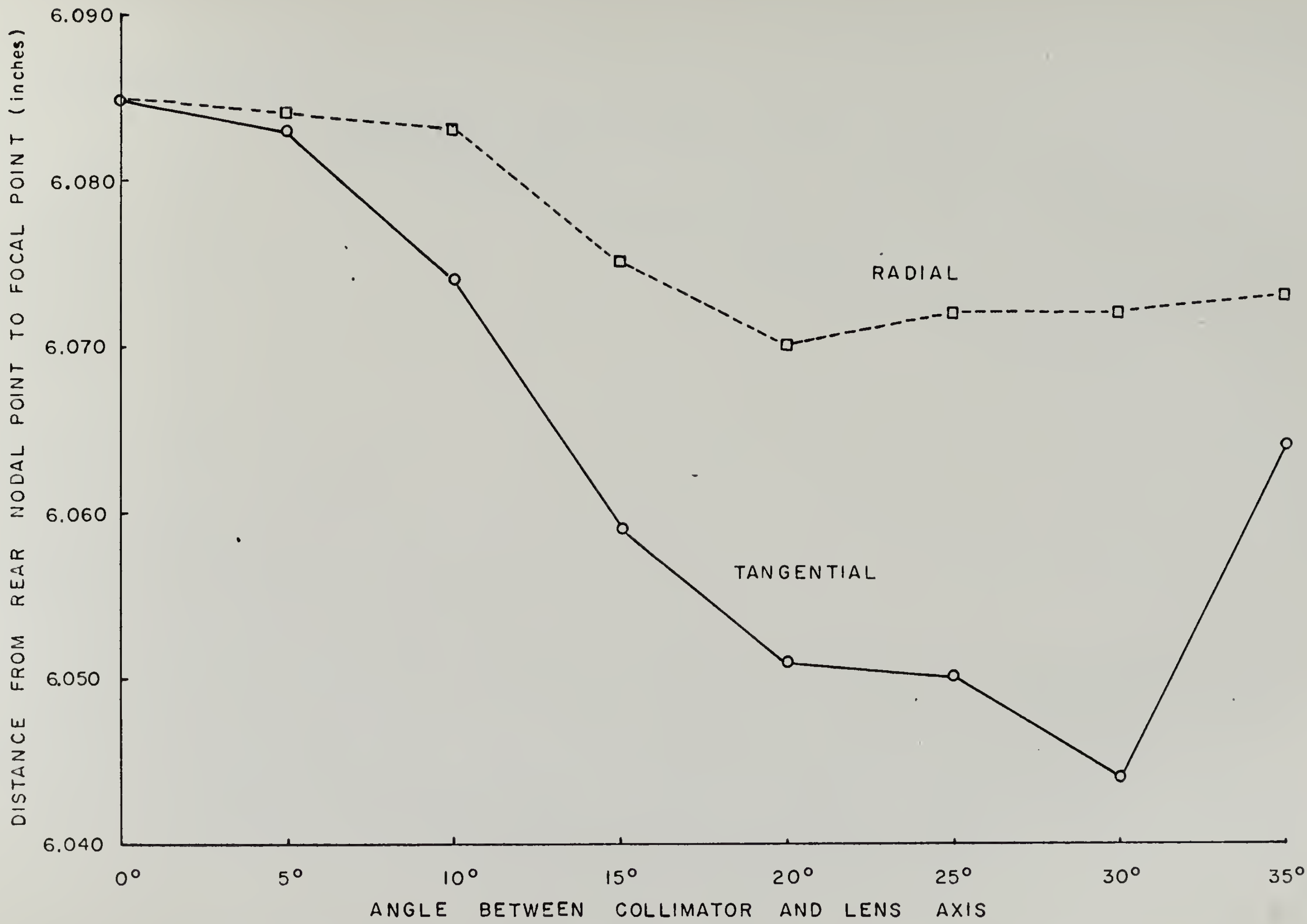


Figure 12. Graph of Results for Best Radial and Tangential Focal Distance for a Metrogon Lens (Focal Length = 6 inches)

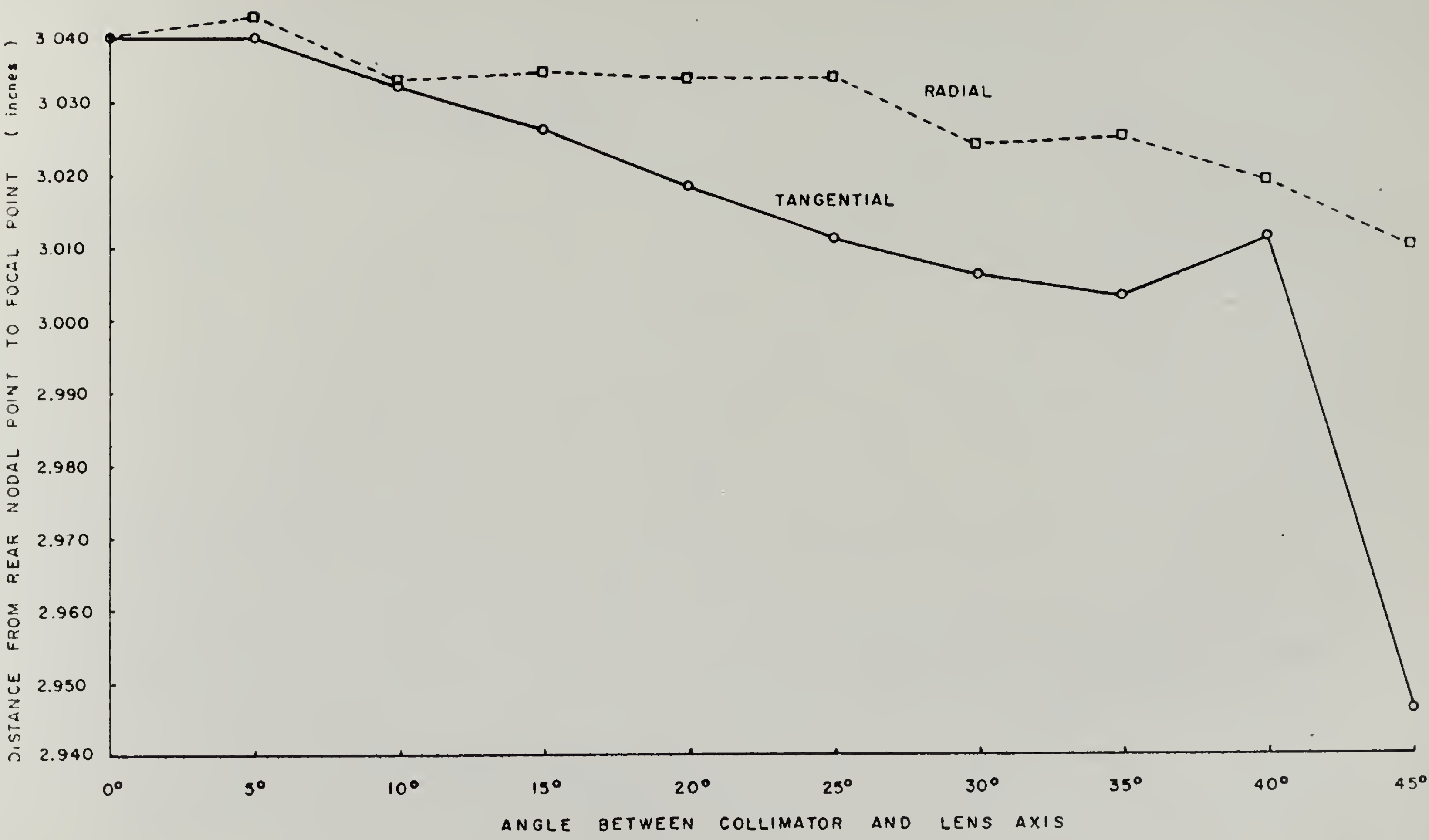


Figure 13. Graph of Results for Best Radial and Tangential Focal Distance for a Metorogon Lens (Focal Length = 3 inches)

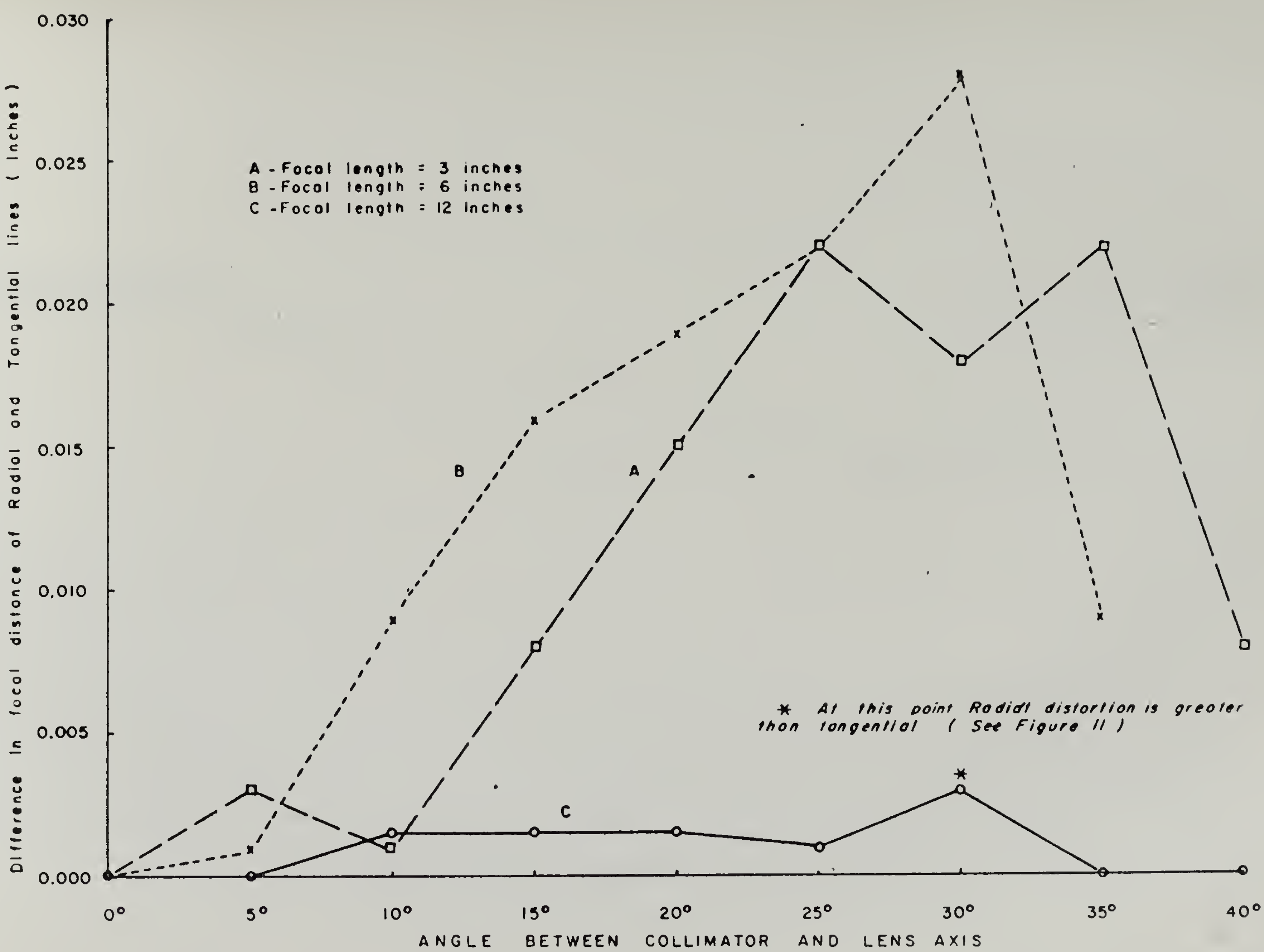


Figure 14. Graph of Comparison of Differences Bewteen Focal Distances of Radial and Tangential Lines for Metrogon Lenses

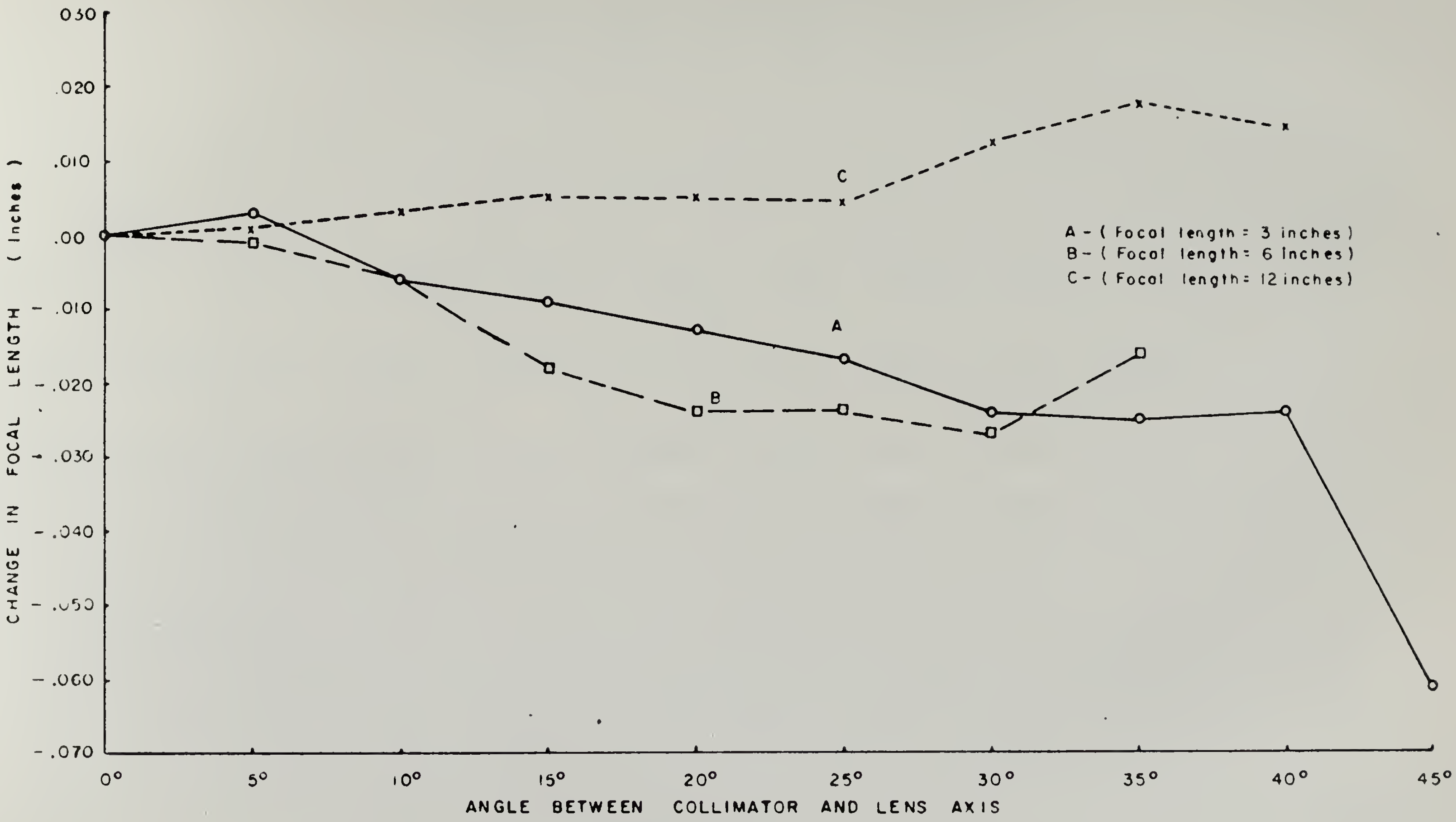


Figure 15. Graph of Curvature of the Field for a Metrogon Lens

TABLE IV

CURVATURE OF FIELD AND ASTIGMATISM COMPUTATIONS

METROGON LENS (focal length = 6 inches)

Angle θ	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°
$\cos\theta$	1.000	.9962	.9848	.9659	.9397	.9063	.8660	.8192		
A (Tan. Focus)	6.085	6.106	6.168	6.273	6.439	6.675	6.979	7.402		
B (Rad. Focus)	6.085	6.107	6.177	6.289	6.459	6.700	7.011	7.413		
$\cos\theta \times A$	6.085	6.083	6.074	6.059	6.051	6.050	6.044	6.064		
$\cos\theta \times B$	6.085	6.084	6.083	6.075	6.070	6.072	6.072	6.073		
Difference	0.000	.001	.009	.016	.019	.022	.028	.009		
Std. Dev.	$\pm$.0004	$\pm$.0006	$\pm$.0008	$\pm$.0010	$\pm$.0011	$\pm$.0014	$\pm$.0017	$\pm$.0024		
Focal Plane	6.085	6.084	6.079	6.067	6.061	6.061	6.058	6.069		
Std. Dev.	$\pm$.0006	$\pm$.0008	$\pm$.0011	$\pm$.0014	$\pm$.0016	$\pm$.0019	$\pm$.0024	$\pm$.0034		

(Tan. = Tangential ; Rad. = Radial ; All measurements in inches)

TABLE V

CURVATURE OF FIELD AND ASTIGMATISM COMPUTATIONS

METROGON LENS (focal length = 3 inches)

Angle θ	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°
cos θ	1.000	.9962	.9848	.9659	.9397	.9063	.8660	.8192	.7660	.7071
A (Tan. Focus)	3.039	3.051	3.079	3.133	3.212	3.322	3.471	3.666	3.931	4.166
B (Rad. Focus)	3.039	3.054	3.080	3.141	3.228	3.347	3.492	3.693	3.941	4.257
cos θ x A	3.039	3.039	3.032	3.026	3.018	3.011	3.006	3.003	3.011	2.946
cos θ x B	3.039	3.042	3.033	3.034	3.033	3.033	3.024	3.025	3.019	3.010
Difference	0.000	.003	.001	.008	.015	.022	.018	.022	.008	.064
Std. Dev.	$\pm$.0002	$\pm$.0008	$\pm$.0008	$\pm$.0010	$\pm$.0012	$\pm$.0013	$\pm$.0012	$\pm$.0020	$\pm$.0025	$\pm$.0057
Focal Plane	3.039	3.041	3.033	3.030	3.026	3.022	3.015	3.014	3.015	2.978
Std. Dev.	$\pm$.0003	$\pm$.0011	$\pm$.0012	$\pm$.0014	$\pm$.0017	$\pm$.0019	$\pm$.0017	$\pm$.0028	$\pm$.0035	$\pm$.0080

(Tan. = Tangential ; Rad. = Radial ; All measurements in inches)

8. RADIAL DISTORTION

8.1 Purpose of Test

This test was conducted to determine if the reduction of the relative aperture of the photogrammetric lenses of different focal lengths had an effect upon the radial displacement of the intersections of light rays upon the image plane from the ideal position of these image points. If there is radial distortion present, it would be equivalent to:

Distortion = $y' - f \tan \alpha$ (for an object at infinity)

y' = the actual radial distance of the image point from the optical axis

f = focal length determined from axial computations

α = the angle of the principal ray in the object space from the lens axis

The radial distortion, if present, is recorded as positive if away from the center, and negative if toward the center of the whole image pattern[2].

8.2 Testing Procedure

A Wild T-4 Goniometer (Figure 6) was used to test the lenses of 3 inch and 6 inch focal lengths. The 12 inch focal length lens was not tested due to the physical size of the test equipment which would have to be modified greatly and also due to lack of comparison data, since this lens was not tested at a relative aperture of f/6.3.

The goniometer was set up on a platform, and the lens was placed in the holding bracket and adjusted so that it was perpendicular to the plane of the test plate holder. The Watts auto-collimator (see

Figure 7) was then positioned about 15 feet in front of the instrument and the goniometer telescope was aligned so that the reticle coincided with the cross hairs of the auto-collimator. The horizontal circle was then set at $0^{\circ}\ 00'\ 00''.0$. Through the use of three adjusting screws and an inside micrometer, it was possible to move the lens perpendicularly along the optical axis until the goniometer telescope pivot axis passed through the front node of the lens. An aperture adjusting diaphgram was fastened to the telescope and a hand comparator was used to observe the diaphragm of the lens. When the lens diaphragm remained in the center of the telescope as the goniometer was swung from side to side, the alignment was correct. A graduated test plate was then mounted in the test plate holder and adjusted until it was perpendicular to the axis of the auto-collimator and the center target of the plate was centered in the telescope.

After the above set up, a thorough check was made and then the angles between the center figure of the target plate and the targets on each of the four diagonals were recorded. This was possible, because, although the goniometer arm was only able to swing in one plane, the target plate was held by rollers and it was possible to rotate this plate 90° [13].

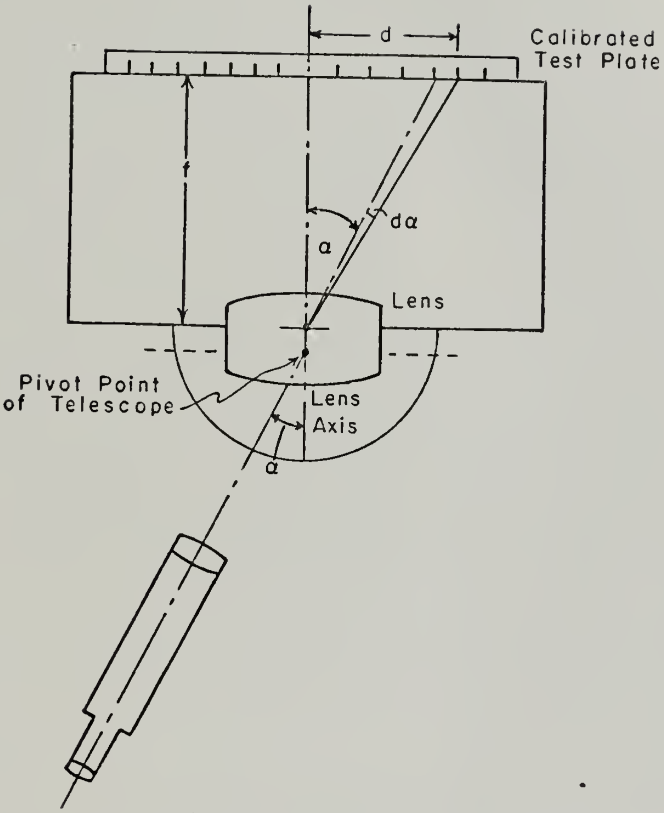


Figure 16. Top View of T-4 Goniometer,
Schematic

Figure 16 shows the physical relationship of the instrument and from this, the simplified computations for the radial distortions are made in accordance with the equations of Section 8.1.

In actual practice, however, the results of these computations yield distortions which were not symmetric about the camera axis. The diagram shown as Figure 17 illustrates the condition of the lens axis not being perpendicular to the test plate.

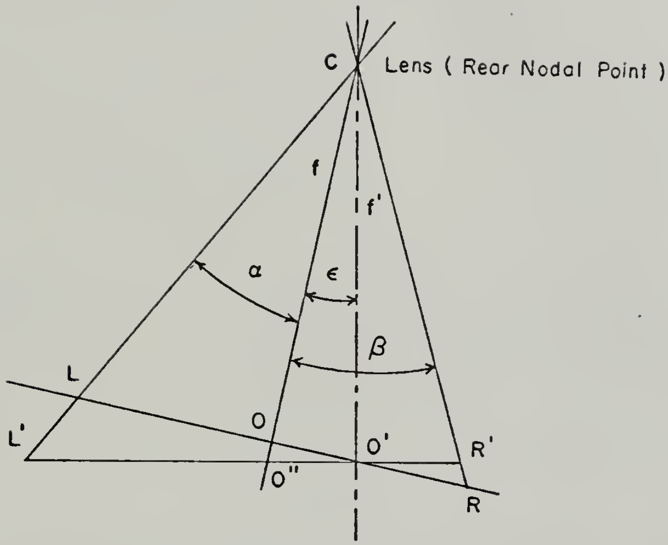


Figure 17. Top View of Tilted Lens Geometry, Schematic

From Figure 17, it can be seen that the line LR represents the test plate and L and R are target images on that plate. Also, angle ϵ is the angle between the lens axis and a perpendicular to the test plate from the rear nodal point of the lens. Therefore, the line OO' is the distance between the center target of the test plate and the axis of symmetry measured on the test plate. If angle ϵ is small, then $OO' \cong f\epsilon$. The line L'R' represents the projections of the two targets on an imaginery plane which is perpendicular to the actual lens

axis and this allows computation of the equivalent distortions at L' and R'. α and β are the measured angles of targets L and R off the telescope axis.

The Equivalent Focal Length of the lens is computed by considering the distortion at the center of the lens to be zero, and from Figure 17,

$$OR = f \cdot \tan \beta; \; OL = f \cdot \tan \alpha$$

$$OR + OL = f(\tan \beta + \tan \alpha)$$

$$f = \frac{OR + OL}{(\tan\beta + \tan\alpha)}$$

The numerical values for OR and OL are taken from the calibrated plate which is supplied by the manufacturer (see page 54)

α and β are measured by the telescope

The radial distortion about the center target is computed as follows:

D'_T = radial distance - $f \cdot \tan \alpha'$

f = equivalent focal length

α' = angle between any target and the center target.

The values for radial distortion are now in hand but to compare them as representative values about a mean, the symmetrical distortion must be balanced. As has been pointed out previously by others[14][4], the graph of the radial distortions about a center target gives the appearance that it is a perfect lens which is tested with a prism in front of it. This gives the curve a "tipped" appearance. As the symmetric distortion curve is what is desired, the following computations are made.

Referring to Figure 17 where D'_T equals the total distortion of any point and assuming angle ϵ is very small,

$$f \cong f' \quad \text{and} \quad OR \cong OR'; \text{ (see following for explanation of } f')$$

thus, the radial distortion for target R =

$$D'_{T_R} = f\cdot\tan\epsilon + f\cdot\tan(\beta-\epsilon) + d'_R - f\cdot\tan\beta$$

where

d'_R = symmetric distortion of R based on equivalent focal length

From Washer's article in PHOTOGRAMMETRIC ENGINEERING[14],

$$\tan\epsilon \cong \epsilon \quad \text{and} \quad \tan^3\epsilon \cong 0$$

and

$$D'_{T_R} = -f\cdot\epsilon\cdot\tan^2\beta + \frac{f\cdot\epsilon^2\cdot\tan\beta}{\cos^2\beta} + d'_R$$

Similarly for target L

$$D'_{T_L} = f\cdot\epsilon\cdot\tan^2\alpha + \frac{f\cdot\epsilon^2\cdot\tan\alpha}{\cos^2\alpha} + d'_L$$

Subtracting:

$$D'_{T_R} - D'_{T_L} = -f\epsilon(\tan^2\alpha + \tan^2\beta) + f\epsilon^2\left(\frac{\tan\beta}{\cos^2\beta} - \frac{\tan\alpha}{\cos^2\alpha}\right) + d'_R - d'_L$$

If $\alpha \neq \beta$ but the difference is less than 2°, the term containing $f\cdot\epsilon^2$ can be ignored[14].

The distance of the axis of symmetry from the center target = $f\cdot\epsilon$.

$$f\cdot\epsilon = -\frac{D'_{T_R} - D'_{T_L}}{\tan^2\beta+\tan^2\alpha} + \frac{d'_R - d'_L}{\tan^2\beta+\tan^2\alpha}$$

If

$$|\alpha-\beta| \ll 1^\circ \quad , \quad \text{then} \quad d'_R - d'_L \cong 0$$

therefore:

$$f\cdot\epsilon = -\frac{D'_{T_R} - D'_{T_L}}{\tan^2\beta + \tan^2\alpha}$$

The symmetric distortion, d'_R and d'_L can be solved in the following manner:

$$d'_R = D'_{T_R} + f\cdot\epsilon\cdot\tan^2\beta - \frac{f\cdot\epsilon^2\cdot\tan\beta}{\cos^2\beta}$$

$$d'_L = D'_{T_L} - f\cdot\epsilon\cdot\tan^2\alpha - \frac{f\cdot\epsilon^2\cdot\tan\alpha}{\cos^2\alpha}$$

To determine the radial distortion for any target based on the calibrated focal length, it is first necessary to compute this length. The method used here is as follows[1]:

f' = Calibrated Focal Length = Effective Focal Length + Δf

$$\Delta f = \frac{D_p + D_n}{\tan\theta_p + \tan\theta_n}$$

Dp = greatest positive distortion (average of all radial distortions)

Dn = greatest negative distortion (average of all radial distortions)

$\tan\theta_p$ = tangent of average angle at which Dp occurs

$\tan\theta_n$ = tangent of average angle at which Dn occurs

The radial distortion for any target, based on calibrated focal length is[13]:

$$d_x = d'_x - \Delta f \tan\alpha'$$

d'_x = d'_R or d'_L as shown above

α' = the angle of the principal ray in the object space from the lens axis

Table VI contains the data and computations for radial distortion of the 3 inch focal length lens as an example. The comparison of the radial distortions of the two lenses at a relative aperture of f/8 to that of the same lenses at a relative aperture of f/6.3 is shown as Figure 18 and 19.

8.3 Comments

The entire method of setting up and recording data in accordance with the instructions given with the instrument[13] was meant to be used with a lens mounted in a lens cone of a camera. Since that was obviously impossible in the test situation, the lenses were tested alone. This is what created the condition of the "tipping" of the lenses slightly about the optical axis and which led to the development of equations for balancing the data. It should be pointed out, however, that the calibration of the camera does not involve refocusing, or other physical change of the camera. It is purely a mathematical procedure to allow the user to adopt a most favorable focal length where the average radial distortion of the image points from their proper position is a minimum. The shape of the distortion curve is the governing criteria in analyzing a photogrammetric lens.

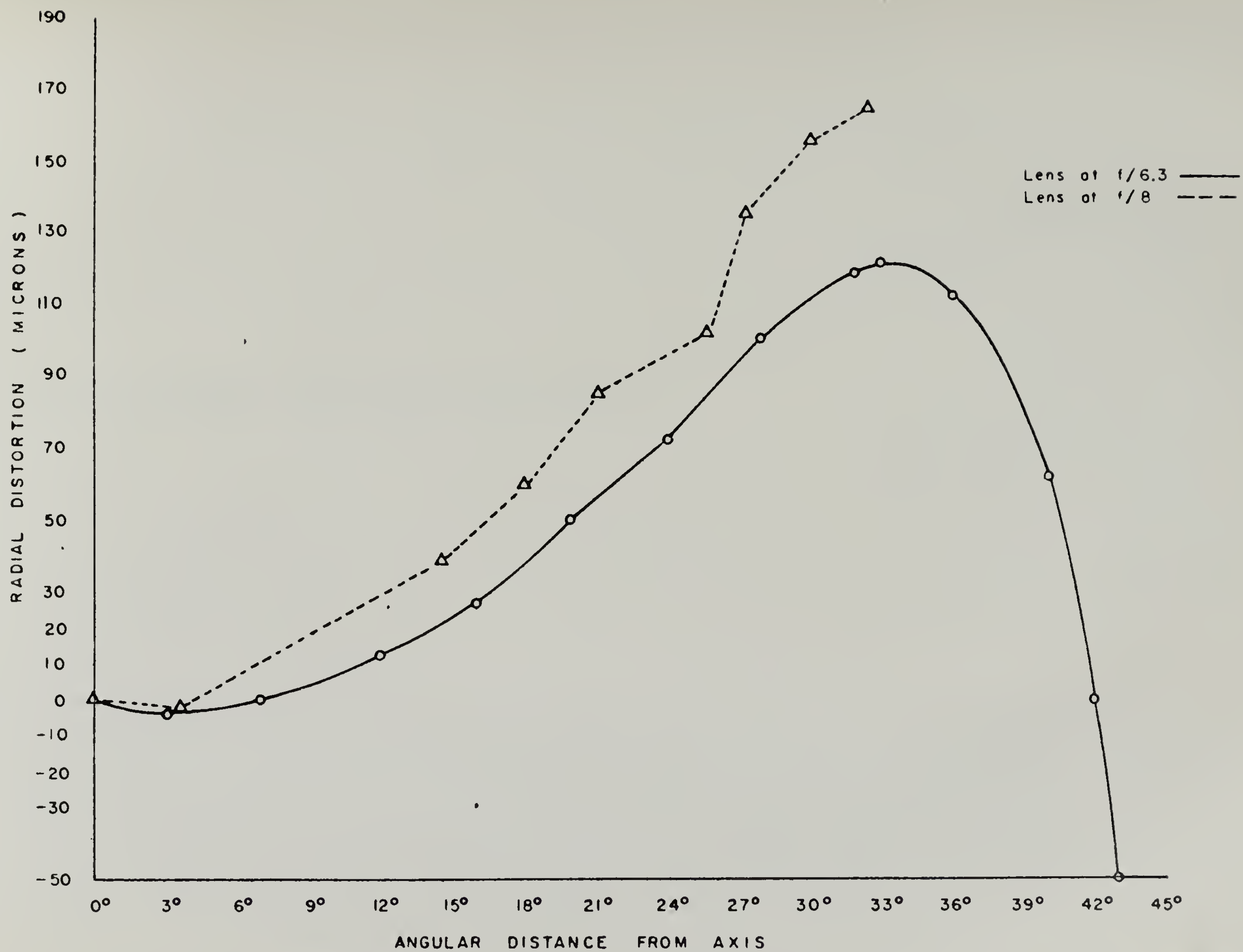


Figure 18. Graph Comparing the Radial Distortion Curve of a Metrogon Lens (focal length = 6 inches) f/6.3, to the Radial Distortion Evaluated for the Same Lens with Relative Aperture f/8

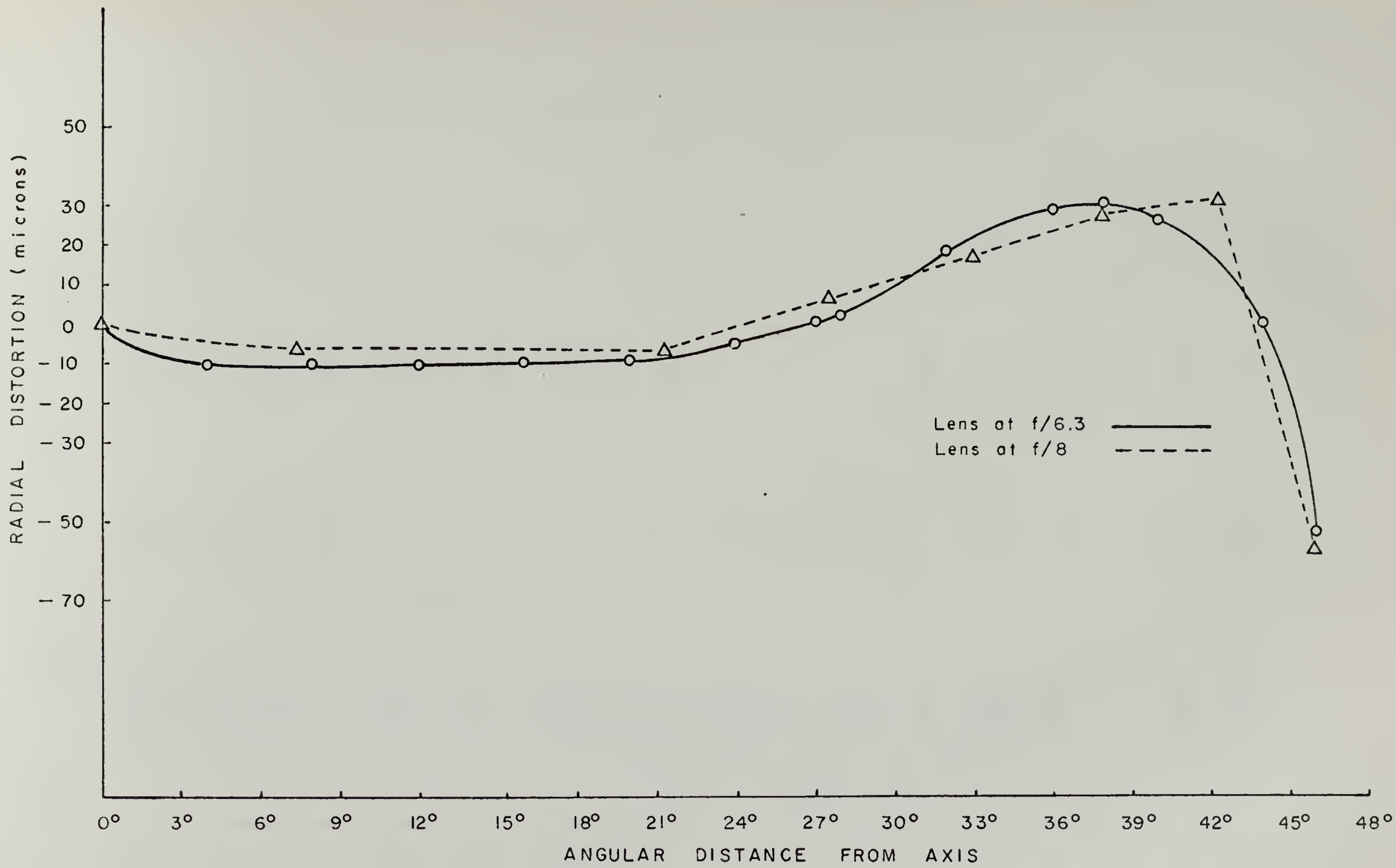


Figure 19. Graph Comparing the Radial Distortion Curve of a Metrogon Lens (focal length = 3 inches) f/6.3, to the Radial Distortion Evaluated for the Same Lens with Relative Aperture f/8

TABLE VI

COMPUTATIONS FOR RADIAL DISTORTION OF A METROGON LENS

(Focal Length = 3 inches)

Goniometer Method

TARGET	α	$\tan\alpha$	$\tan^2\alpha$	$\cos\alpha$	$\cos^2\alpha$	$f\tan\alpha$	$D'T - D - f\tan\alpha$	$D'T_R - D'T_L$	$\tan^2\alpha_R + \tan^2\alpha_L$	f_e	$f_e\tan^2\alpha$	$f_e^2\tan\alpha\cos^2\alpha$	$d'x$	$D_{efX(ave)}$ 2 diag.	$\Delta f\tan\alpha$	dx	$dx(ave)$ 4 diag.
Diag.E (left)																	
7																	-.0565
6	42-19-41	.910825	.82960	.739301	.54657	69.8138	.1828				.1136	.0312	.0380	.0354	.0256	.0124	.0313
5	37-58-28	.780566	.60928	.788285	.62139	59.8296	.1693				.0834	.0235	.0624	.0626	.0221	.0403	.0272
4	33-03-10	.650718	.42343	.838169	.70253	49.8769	.1201				.0580	.0173	.0448	.0468	.0184	.0264	.0165
3	27-30-48	.520801	.27123	.886926	.78664	39.9189	.0770				.0371	.0124	.0275	.0270	.0147	.0128	.0063
2	21-21-03	.390906	.15281	.931368	.86745	29.9626	.0330				.0209	.0084	.0037		.0111	-.0074	-.0074
1	07-25-55	.130444	.01702	.991599	.98327	9.9984	-.0015				.0023	.0025	-.0063	-.0026	.0037	-.0100	-.0062
Diag.G (right)																	
1	07-27-54	.130439	.01701	.991600	.98327	9.9980	.0014	.0029	.0340		.0023	.0025	.0012		.0037	-.0025	
2																	
3	27-33-17	.521782	.27226	.886569	.78600	39.9941	.0017	-.0753	.5435	+.1386	.0373	.0124	.0266		.0148	.0118	
4	33-06-42	.652182	.42534	.837608	.70159	49.9891	.0077	-.1124	.8488	+.1324	.0582	.0174	.0485		.0185	.0300	
5	38-03-03	.782715	.61264	.787464	.62010	59.9943	.0025	-.1668	1.2219	+.1365	.0839	.0236	.0628		.0222	.0406	
6	42-25-23	.913864	.83515	.738184	.54492	70.0468	-.0502	-.2330	1.6648	+.1400	.1143	.0314	.0327		.0259	.0068	
7	46-16-26	1.045486	1.09304	.691212	.47777	80.1355	-.1390				.1496	.0409	-.0303		.0296	-.0599	

$f_{eG} = \frac{19.9963}{.260883} = 76.649$ mm ; $f_{e(ave)} = .1369$; $f_e^2 = .0187$; $\Delta f = (\frac{.055 - .003}{1 + .8391}) = +.0283$

TARGET	α	$\tan\alpha$	$\tan^2\alpha$	$\cos\alpha$	$\cos^2\alpha$	$f\tan\alpha$	$D'T - D - f\tan\alpha$	$D'T_R - D'T_L$	$\tan^2\alpha_R + \tan^2\alpha_L$	f_e	$f_e\tan^2\alpha$	$f_e^2\tan\alpha\cos^2\alpha$	$d'x$	$D_{efX(ave)}$ 2 diag.	$\Delta f\tan\alpha$	dx	$dx(ave)$ 4 diag.
Diag.F (right)																	
7	46-15-28	1.044898	1.09181	.691415	.47805	80.0935	-.0971	-.2185	2.1777	+.1003	.1471	.0396	.0104		.0296	-.0192	
6	42-24-26	.913357	.83422	.738370	.54519	70.0106	-.0130	-.2435	1.6627	+.1465	.1124	.0303	.0691		.0259	.0432	
5	38-02-18	.782364	.61209	.787599	.62031	59.9698	-.0276	-.1174	1.2218	+.0961	.0825	.0228	.0321		.0221	.0100	
4	30-05-55	.651857	.42492	.837732	.70179	49.9661	.0304	-.0801	.8485	+.0944	.0572	.0168	.0100		.0185	-.0085	
3	27-32-52	.521627	.27209	.886625	.78610	39.9838	.0132	-.0551	.5434	+.1014	.0367	.0120	.0115		.0148	-.0033	
2																	
1	07-26-00	.130469	.01702	.99156	.98326	10.0007	-.0038	-.0075	.0340		.0023	.0024	-.0039		.0037	-.0076	
Diag.H (left)																	
1	07-25-44	.130390	.01700	.991606	.98328	9.9947	.0037				.0023	.0024	-.0010	-.0025	.0037	-.0047	
2																	
3	27-30-55	.520906	.27134	.887888	.78835	39.9285	.0683				.0366	.0120	.0197	.0156	.0147	.0050	
4	33-03-26	.650828	.42358	.838126	.70246	49.8873	.1105				.0571	.0168	.0366	.0233	.0184	.0182	
5	37-59-01	.780825	.60969	.788187	.62124	59.8518	.1450				.0821	.0228	.0401	.0361	.0221	.0180	
6	42-20-21	.910180	.82843	.739171	.54637	69.7671	.2305				.1116	.0302	.0887	.0789	.0258	.0629	
7	46-10-48	1.042062	1.08589	.692395	.47941	79.0761	.1214				.1463	.0393	-.0642	-.0269	.0295	-.0937	

$f_{FH} = \frac{19.9953}{.260859} = 76.652$ mm ; Effective Focal Length$_{(ave)}$ = 76.651 mm ; $f_{e(ave)} = +.1347$; $f_c^2 = .0181$

9. CONCLUSIONS AND RECOMMENDATIONS

The normal method for reducing the amount of light to which a film is exposed during the taking of a photogrammetric picture is to increase the speed of the camera shutter. The conditions requiring reduced light as well as the limitations of shutter speed and efficiency are not subjects of this study, however, they do exist[11]. The light causing the film exposure can be decreased by reducing the relative aperture of the lens rather than by limiting the exposure time with a faster shutter speed. This research was undertaken to investigate the effect upon the image distortions caused by a reduction of relative aperture. Several different focal lengths of the same type lens were considered in order to give comparisons for use when selecting a photogrammetric camera of "best" focal length for a specific image purpose.

The lens distortions which were investigated are the major contributors to image inaccuracies[5]. Each is considered in turn and a comparison is made between the specific lens distortions for the same three Metrogon lenses of varying focal lengths at relative apertures of f/6.3 and f/8. The conclusions are not general but are limited to this specific set of Metrogon lenses.

9.1 Longitudinal Chromatic Aberration

The longitudinal chromatic aberration was significantly reduced by the reduction of relative aperture. The reduction of this aberration was about 25% throughout the visible wave length range due to the reduction of relative aperture from f/6.3 to f/8. This aberration increased linearly with increased focal length. Thus, the value of aberration for the lens of focal length 12 inches was almost four times greater than

that of the lens with focal length of 3 inches. Similarly, the lens of 6 inch focal length has about twice the value of longitudinal aberration as that with focal length of 3 inches.

9.2 Longitudinal Spherical Aberration

A significant reduction in longitudinal spherical aberration with decreased relative aperture is also apparent. The amount of this reduction decreases with increasing focal length. The amount of longitudinal spherical aberration follows this pattern:

	f/6.3	f/8
3 inch focal length	4	1
6 inch focal length	2	1
12 inch focal length	1.5	1

9.3 Astigmatic Difference

The change of astigmatic difference due to decreased relative aperture is difficult to assess for the lens of 12 inch focal length. This is due to the difficulty in analyzing the negatives obtained by the method of testing. It appears that the astigmatic difference is reduced about 50% throughout the range of observation. The lens distortion for the lenses of 3 inch and 6 inch focal lengths appear to be unchanged. This distortion is greatest for the lens of 6 inch focal length and this is probably a characteristic of this particular lens.

9.4 Curvature of the Field

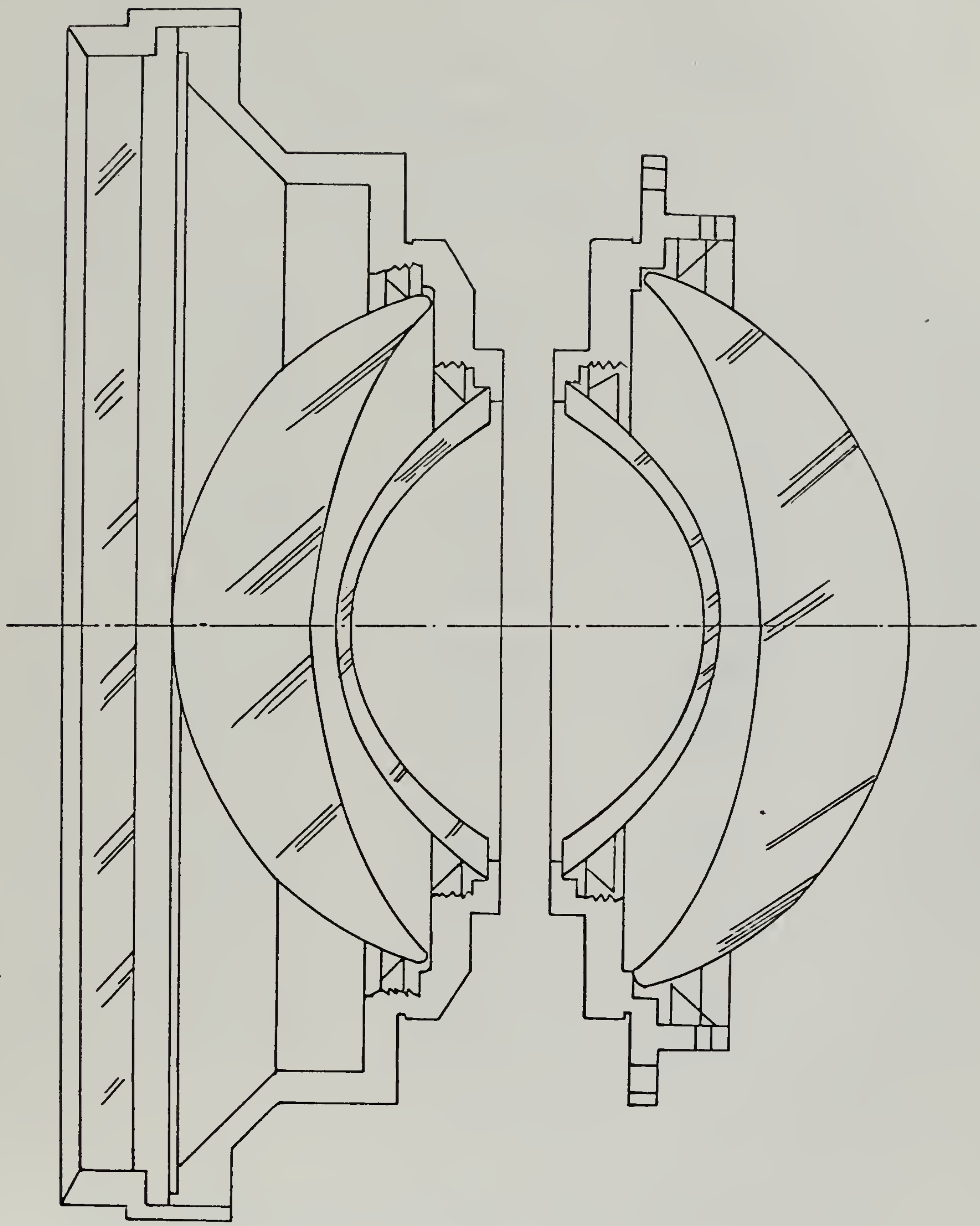
The distortion caused by curvature of the field is reduced for all lenses only very close to the lens axis. After an angle of 5°- 10° off the lens axis, the curvature of the field for all lenses increases

for the test with reduced relative aperture. Although the linearity of the curves improve somewhat, they still follow the general pattern of the curves computed prior to aperture reduction. This effect is probably caused by increased depth of field for the decreased relative aperture.

9.5 Radial Distortions

The radial distortion for the lens is not significantly changed by the decrease in relative aperture. The difference noted for the lens of 6 inch focal length could be due to approximations in calibrated focal length in reducing the distortion curve to compare with the data of the comparison study. Only retesting with a different test apparatus, which would allow the measuring of more target points, could give definite results on this point.

APPENDIX



E.F.L. 153 ± 2.5 mm Approx. Scale 2:1

Construction Line Diagram of Metrogon Lens

CALIBRATION OF WILD T-4 GONIOMETER*

Distances from Central Target
(Graduated Plate No. 13224-104)

(In millimeters)

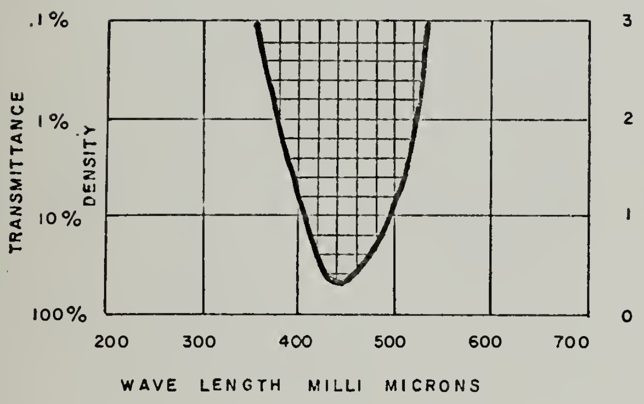
Target	Diagonals			
	E	F	G	H
1	9.9969	9.9969	9.9994	9.9984
2	19.9972	19.9967	19.9982	19.9982
3	29.9959	29.9959	29.9963	29.9966
4	39.9959	39.9970	39.9958	39.9968
5	49.9970	49.9965	49.9968	49.9978
6	59.9989	59.9974	59.9968	59.9968
7	69.9966	69.9976	69.9966	69.9976
8	79.9964	79.9964	79.9965	79.9975
9	89.9980	89.9975	89.9968	89.9963
10	99.9974	99.9969	99.9965	99.9975
11	104.9975	104.9980	104.9967	104.9977
12	109.9985	109.9985	109.9968	109.9980
13	114.9976	114.9981	114.9964	114.9974
14	119.9971	119.9976	119.9970	119.9970
15	124.9996	124.9996	124.9984	124.9998
16	129.9999	129.9999	129.9980	129.9990
17	134.9993	135.0003	134.9981	134.9986
18	139.9995	139.9995	139.9991	139.9994
19	144.9986	144.9996	144.9983	144.9983
20	149.9994	149.9994	149.9985	149.9990
21	155.0002	154.9992	154.9993	155.0007
22	159.9992	159.9992	160.0007	160.0007
23	162.0013	162.0010	162.0012	162.0018

*These are calibration figures given by the Wild Company. They were considered accurate to .001 mm.

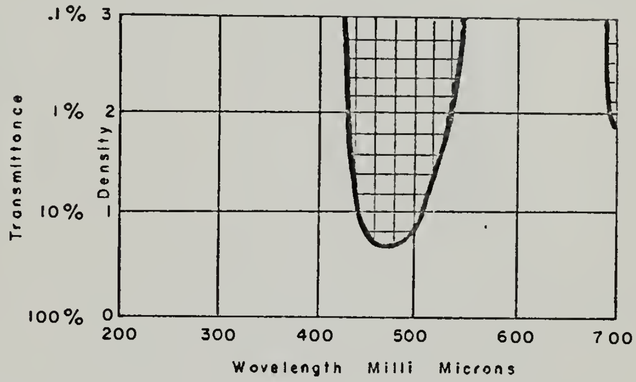
FILTER CHARACTERISTICS

(Kodak Wratten : Data from Kodak)

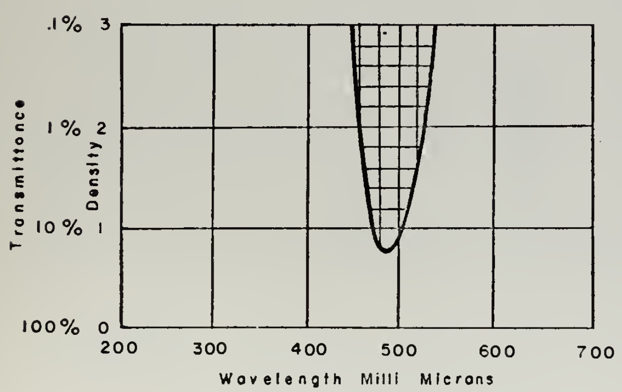
Number 47
Dominant Wave Length 470.1



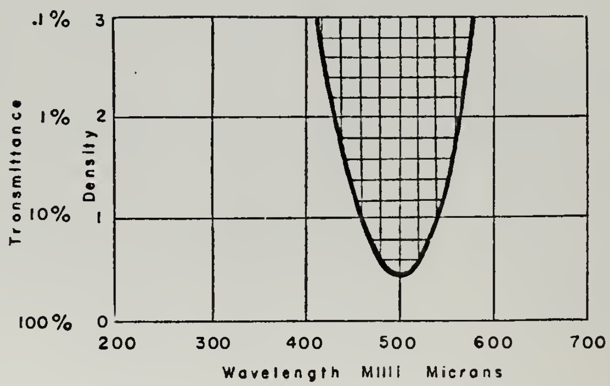
Number 45a
Dominant Wave Length = 483.5



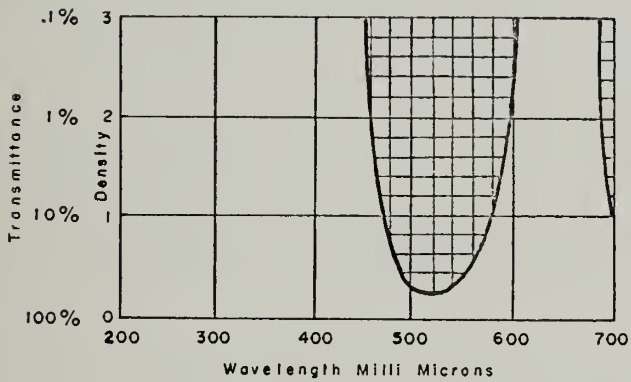
Number 75
Dominant Wave Length = 490.5



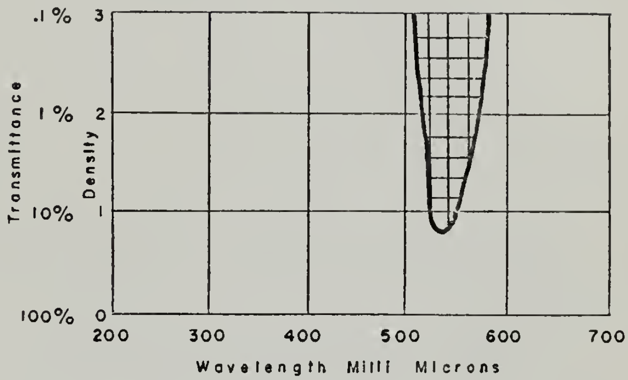
Number 65
Dominant Wave Length = 501.3



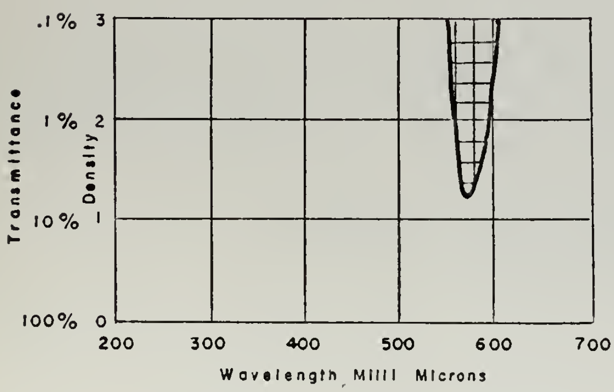
Number 60
Dominant Wave Length = 520.0



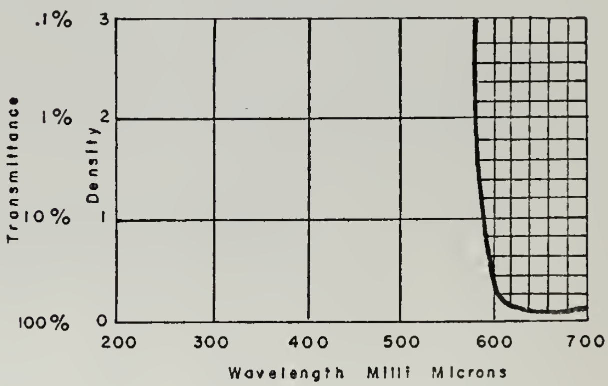
Number 74
Dominant Wave Length = 538.0



Number 73
Dominant Wave Length = 576.0



Number 25
Dominant Wave Length = 617.2



USAF RESOLVING POWER TEST TARGET 1951, #1 and #2

1. The USAF Resolving Power Test Target 1951, #1 and #2, consists of 9 or 10 target groups, respectively, every two target groups forming a square. There are 5 squares of different size, the smaller squares being inside the next larger ones. Every target group consists of 6 target elements.

2. The groups are designated by group numbers k. For example k is -2, -1, 0, 1, and so on.

3. The elements are designated by element numbers n, n is equal to 1, 2, 3, 4, 5, 6.

4. The dimensions of the elements are such that the element number n within group number k represents a resolving power

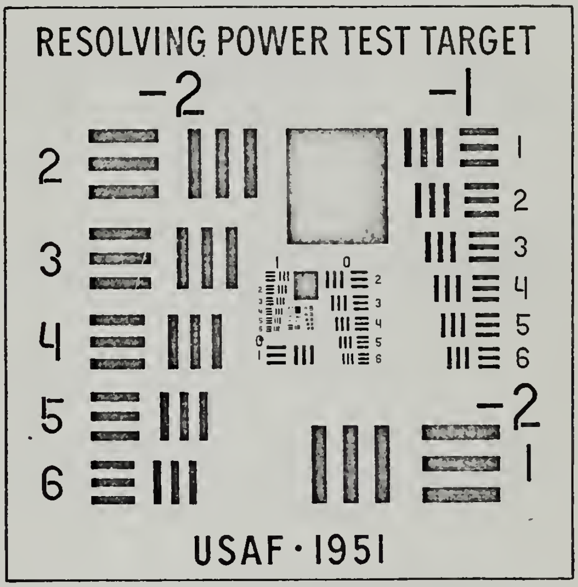
$R = 2^{\frac{(k + n-1)}{6}}$ lines per millimeter. For example, element #1 in group #-2

represents a resolving power of R-0.25 lines/mm. This element is the largest one of the entire target.

5. The resolving power of elements having the same element number, but belonging to groups of subseqent group numbers differ by the factor 2. Thus, element #1 in group #-1 represents 0.5 lines/mm, element #1 in group #0 represents 1 lines/mm, and so on.

6. Within a group, the resolving powers in subsequent elements differ by a factor 1.122 (equal to sixth root of two). The following factors apply to the relative resolving power within a group:

Element #1	1.000
2	1.122
3	1.260
4	1.414
5	1.587
6	1.781



7. By multiplication of these figures with the factors 0.25; 0.5; 1.0; 2; 4; and so on, the resolving power for every element of the target can be obtained. The following table contains the equivalent resolving power in lines per millimeter for each target element.

Number of Lines per Millimeter in USAF
Resolving Power Test Target 1951,#1 and #2
GROUP NUMBER (k)

Element No. (n)	-2	-1	0	1	2	3	4	5	6	7
1	0.25	0.50	1.00	2.0	4.0	8.0	16.0	32.0	64.0	128.0
2	.28	.56	1.12	2.2	4.5	8.9	18.0	35.9	71.8	144.7
3	.32	.63	1.26	2.5	5.0	10.1	20.2	40.3	80.6	161.3
4	.35	.71	1.41	2.8	5.7	11.3	22.6	45.3	90.5	181.0
5	.40	.79	1.59	3.2	6.4	12.7	25.4	50.8	101.6	203.2
6	.44	.89	1.78	3.6	7.1	14.3	28.5	57.0	114.0	228.1

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